Report # 5: Ecosystem and Tree Species Bioclimate Envelope Modeling for the West Kootenays

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1.0 INTRODUCTION

Recent reports by the International Panel on Climate Change (IPCC) have confirmed that global climate change is underway, and likely to accelerate over the coming decades unless humans make drastic cuts to global greenhouse gas (GHG) emissions (IPCC 2007). Analysis of climate data collected over the last century has confirmed that parallel climatic changes are occurring in BC (Spittlehouse 2008), and in the Columbia Basin (Murdock et al. 2007, Utzig 2011). Depending on assumptions about future GHG emissions, results from downscaled global climate models (GCMs) illustrate a range of potential climate changes for BC over the next century. These include increases in annual temperatures and precipitation, decreases in summer precipitation in southern BC, changes in snowpack, increases in annual climate variability and increases in the frequency and magnitude of extreme weather events.

The British Columbia government has recognized that the uncertainties associated with climate change demand a forest management approach that differs from the traditional (MoFR 2008). With the establishment of the Future Forest Ecosystems Initiative (FFEI) in 2006, the province began a move toward adapting the forest and range management framework, and addressing management issues that arise from climate change. The province established the Future Forest Ecosystem Scientific Council[1] (FFESC) in 2008 to deliver research grants to support the objectives of the FFEI. This report summarizes some of the findings of one project[2] that was among those funded by the FFESC under their 2009 call for proposals.

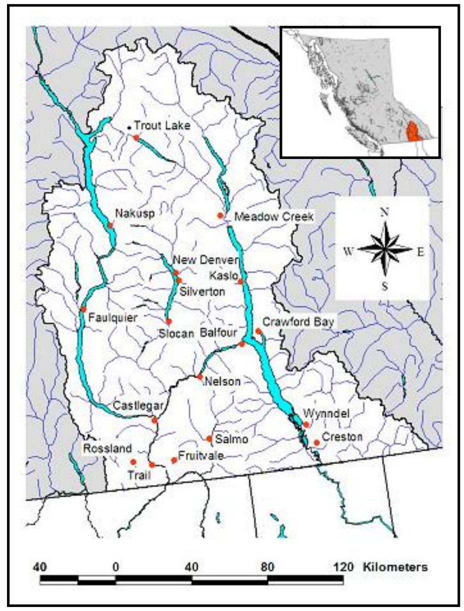


Figure 1.1. Study area.

As climatic change proceeds, it will directly impact ecosystems and species distributions, creating conditions unsuitable for some currently occurring species, and ones more suitable for other species not able to survive here today. Changing climate will also affect disturbance regimes (Dale et al. 2001, Littell et al. 2009), such as fire (Utzig et al. 2011, Littell et al. 2010, Flannigan et al. 2005), insect and disease outbreaks (Woods et al. 2010) and windthrow (Guthrie et al. 2010, Blennow and Olofsson 2008), all of which will also impact the future distribution of species and ecosystems in the West Kootenays.

One tool used to better understand the potential changes to ecosystems is bioclimate modeling, otherwise known as climate envelope modeling. Of particular interest are a class of species distribution models called "niche models," and their application to "bioclimate envelopes". These models use machine learning and various statistical analyses to correlate ecosystems with environmental factors, including climate, and then predict where ecosystem niches may occur under future climates (Mbogga et al. 2010).

Acknowledgements

Andreas Hamann has been directing a number of graduate students at the University of Alberta in Edmonton in application and assessment of climate envelope models for various forestry applications in Western Canada. Two graduate students, David Roberts and Laura Gray, have kindly provided technical assistance, and some of their modeling outputs as a basis for this report. Their data and advice has been essential for this assessment, but any shortcomings are the responsibility of the author.

[1] Further information on FFESC: http://www.for.gov.bc.ca/hts/future_forests/council/index.htm

[2] Resilience and Climate Change: Adaptation Potential for Ecological Systems and Forest Management in the West Kootenays. For further information on the project: http://kootenayresilience.org

2.0 METHODS

The methods selected for this assessment represent an exploration of a range of approaches to examining potential changes in ecosystems resulting from projected climate change. A principle concern is trying to understand the level of uncertainty associated with these projections (Mbogga et al. 2010). Two main sources of uncertainty are: 1) the differences between the General Circulation Models (GCMs) used for projections, and 2) assumptions about future GHG emissions. There are two commonly employed approaches to dealing with these uncertainties. One approach is to select a limited number of scenarios for illustrative purposes, in an attempt to portray the range of potential climate projections. We have used this approach for assessing bioclimate envelope projections, utilizing three scenarios that represent the Warm/ Moist, Hot/ Wet, Very Hot/ Dry edges of the range of projections for BC (Murdock and Spittlehouse 2011). The second approach is to run a number of GCMs and/or GCM emission scenarios, an "ensemble", and then report the average of the outputs. This approach was employed for summarizing projections for changes in tree species bioclimate envelopes. A third source of uncertainty are the methods used to link projected changes in climate to potential ecosystem changes, given that climate is only one factor in determining ecosystem structure and composition (Major 1951). Although bioclimate models do not directly address ecosystem processes or population dynamics, they do model "realized niches," and therefore the effective results of these processes are captured in the analysis of present conditions.

The future time period for reporting is another important factor to consider when assessing bioclimate envelope projections. Because most harvesting rotations for forest management in our study area range between 80 and 120 years, we have chosen to concentrate on projections for the 2080s (averages of 2071-2100). However, it is also important to understand how the climate changes through time, and we have therefore presented the tree species projections and one ecosystem scenario projection for the 2020s, 2050s and 2080s.

Ecosystem and tree species bioclimate envelope projections were obtained from the Andreas Hamann research group at the University of Alberta, Edmonton. Detailed descriptions of the methods employed for projecting the future spatial distribution of bioclimate envelopes can be found in Hamann and Wang (2006), Mbogga et al. (2010), Roberts and Hamann (2011) and Gray and Hamann (2011). The following is a brief summary of those descriptions, with more detailed information in Appendix 1.

2.1 Bioclimate Envelope Projections

The analysis involved five steps:

1. Selection of Climate Scenarios

Three climate scenarios were selected for examining the range of projected changes in bioclimate envelopes for the study area (see Table 2.1). The scenarios selected are consistent with recommendations for illustrative purposes in BC by Murdock and Spittlehouse (2011). A fourth scenario was also analyzed to look at projected changes through time, and these results are summarized Appendix 3. To simplify discussion in the report, the three scenarios will be referred to by their descriptive names. The reference period chosen for comparison is 1961-1990. It should be noted that recent trends in CO_2 emissions exceed the rates projected by all of these scenarios (Sheehan 2008). For further information on GCMs and emission scenarios relevant to this study, see the Report #3 on climate projections (Utzig 2011 - available at www.kootenayresilience.org).

Table 2.1. Summary of climate scenario characteristics.

Descriptive Name	GCM/ Emission Scenario/ Run	Modeling Source	BC Projection Comparison	Emissions Trajectory	CO_2 Emission Scenario Assumptions
Warm/ Moist	HadCM3_B1_r1	Hadley Centre for Climate Prediction and Research, Met Office (UK)	Lower warming; minimal increase in annual precip.	Low and growing very slowly; beginning to decrease by the 2050s	Increases in global social/cultural harmony, with economic growth and technological development shifting to an emphasis on sustainability
Hot/ Wet	CGCM3_A2_r1	Canadian Centre for Climate Modeling and Analysis (Canada)	Moderate warming; greatest increase in annual precip.	Moderate to high and continuously increasing	Slow regionalized economic growth and technological advancement, continued use of fossil fuels
Very Hot/ Dry	HadGEM_A1B_r1	Hadley Centre for Climate Prediction and Research, Met Office (UK)	Most warming; moderate decrease in annual precip.	Moderate to high and growing; beginning to decrease by the 2060s	Rapid economic growth, technological advances, increased energy efficiency and a balance between fossil fuels and non-fossil fuels

2. Definition of Bioclimate Envelopes

Bioclimate envelopes were established by linking spatially defined climate variables with current ecosystem mapping. To establish current climate variables, the Hamann group acquired monthly climate data for western North America (west of 100^o W long.) for the 1961-90 period from ClimateWNA[3]. The data was assigned to a 1 km grid for the western NA study area (approx. 10 million points). Ten of the least inter-correlated and biologically-relevant variables were chosen for the analysis. Ecosystem classification and mapping systems covering the same area were combined to create a spatial coverage of 770 individual ecosystem mapping units. The RandomForest modeling tool was employed to identify multi-dimensional bioclimate envelopes for each ecosystem unit.

3. Projections of Future Climate Conditions

Future climate characteristics for each grid cell, under each scenario described above, were established using ClimateWNA data. Classification of the projected future climate at each grid point under each scenario was determined by utilizing RandomForest to reclassify the future climate data for each grid point, based on the climatic profiles established from analyzing each of the ecosystems in relation to their reference period climate profiles. Comparative mapping of ecosystem distribution for the West Kootenay study area (referred to as "Current Mapping" was derived from the latest version of Biogeoclimatic Ecosystem Classification (BEC) mapping for British Columbia (Meidinger and Pojar 1991; Version 7 with recent updates - D. MacKillop pers. com.).

[3] Available at: http://www.ales2.ualberta.ca/RR/people/hamann/data.html and http://www.genetics.forestry.ubc.ca/cfcg/climate-models.html

4. Consolidation of Ecosystem/ Bioclimate Units

To simplify reporting and partially compensate for the differences between the various classification systems, we have consolidated the 770 ecosystem units into more generalized types, with reporting at a higher hierarchical level of classification. The generalized ecosystem types[4] are:

- **Alpine (Alp)**: alpine tundra (e.g., IMA, CMA)
- **Alpine transition (Atran)**: parkland/ woodland alpine transition (e.g., ESSFdmp, ESSFvcw)
- **Wet ESSF (W ESSF)**: wet Engelmann spruce-subalpine fir forest (e.g., ESSFvc)
- **Dry ESSF (D ESSF):** dry Engelmann spruce-subalpine fir forest (e.g., ESSFdm)
- **CWH**: coastal western hemlock forest (e.g., CWHmm)
- **Coast transition (Ctran):** coastal transition cedar-hemlock forest (e.g., CWHds, ICHmc)
- **MSW**: wet montane/ sub-boreal spruce forest (e.g., SBSmc)
- **MSD:** dry montane/ sub-boreal spruce forest (e.g., SBPS, SBSdw, MSdk)
- **Wet ICH (W ICH):** wet interior cedar-hemlock forest (e.g., ICHvk)
- **Moist ICH (M ICH):** moist interior cedar-hemlock forest (e.g., ICHmw)
- **Dry ICH (D ICH):** dry interior cedar-hemlock forest (e.g, ICHdw)
- **Grand Fir (GF)**: grand fir – Douglas-fir forest (e.g., ICHxw)
- **Wet IDF (W IDF)**: wet interior Douglas-fir forest (e.g., IDFww)
- **Dry IDF (D IDF):** dry interior Douglas-fir forest (e.g., IDFdm)
- **Ponderosa Pine (PP)**: ponderosa pine forest and grassland savanna (e.g., PP)
- **Grassland-Steppe (GS)**: grassland and steppe (e.g., BG)

5. Assessment for Novel Bioclimate Envelopes

When assessing climate projections for individual grid cell locations, RandomForest assesses all of the reference period bioclimate envelopes from across western NA, and then selects the bioclimate envelope that is most similar, based on averaging the results of multiple classification trees. However RandomForest does not indicate how similar the two combinations of climate data actually are. Calculations of Mahalanobis distance (Mahalanobis 1936) were used to assess the similarity between projected combinations of climate variables and the reference period bioclimate envelope selected by RandomForest (Roberts and Hamann 2011). A minimum Mahalanobis distance of less than one indicates a relatively good match between the future climate and a reference period ecosystem climate envelope somewhere in western NA, while a distance greater than one indicates a novel or non-analogue combination of climate variables, increasingly novel as the Mahalanobis distance increases beyond one. These distances were then displayed on maps to identify areas for which potentially novel climates are projected.

2.2 Tree Species Climate Envelope Projections

Individual tree species climate envelope projections were determined by adding additional information to the results of the ecosystem bioclimate envelope projections (Gray et al. 2011). This analysis followed the approach for projecting bioclimate envelopes described above, but added additional climate scenarios, and additional data on

[4] A comprehensive description of how the ecosystem types were consolidated is available at: www.kootenayresilience.org .

the occurrence of individual tree species in the 770 ecosystem units. The modifications and additional steps included:

1. Selection of Climate Scenarios

The tree species climate envelope projections were completed for combinations of five GCMs: CGCM2 – Canada, HADCM3 – UK, ECHAM4 – Europe, CSIRO2 – Australia, and PCM - United States; and four emission scenarios: A1FI, A2, B1, B2. Two GCM/ emission scenario combinations were not available (ECHAM4_A1F1 and ECHAM4_B1), leaving 18 total runs.

2. Assessment of Current and Projected Distribution of Tree Species Bioclimate Envelopes

Forest inventory mapping was used to determine the current frequency of individual tree species occurrences for each of the 770 ecosystem units. These species frequencies were then applied to each grid cell under each scenario, in accordance with the projections of bioclimate envelope projections for that grid cell. The output data are summarized through maps displaying average frequencies projected from the 18 GCM/ scenario combinations for each species at each grid cell at four time periods (current mapping, 2020s, 2050s, 2080s). As a general indication of confidence for the average projections, an additional map for each species and future time period is provided showing the level of agreement between the 18 scenarios with regard to presence and absence of the species.

3.0 RESULTS

For the purposes of analysis and reporting the study area has been split into three subregions[5]: North, Mid and South (see Figure 3.1). Each of the subregions has somewhat unique topographic and climatic characteristics, with temperature decreasing, and precipitation, relief, and ruggedness increasing from South to North.

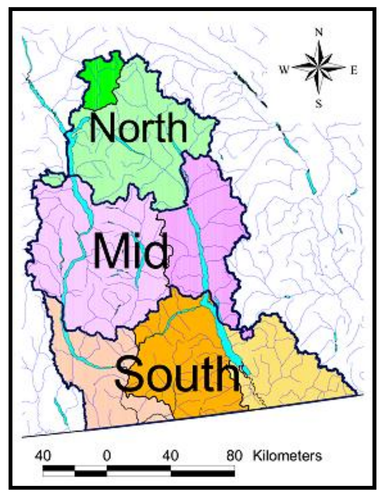


Figure 3.1. Subregions.

The results section begins with a description of the projected changes in seasonal temperature and precipitation for each of the scenarios to get a sense of which climatic factors may be driving the projected changes in bioclimate envelopes. Subsequently, maps and descriptions of the projected bioclimate envelope shifts are presented for each of the scenarios (more detailed maps are provided in Appendix 2). This is followed by a description of the assessment for novel bioclimate envelopes for each of the scenarios. Lastly the results of the ensemble analysis for projected tree species shifts are presented. The following discussion section provides some context for the results by comparing and contrasting these results with other studies and sources of information on potential climate change impacts. Appendix 3 provides an in-depth discussion of a timeline of changes projected by an additional scenario.

3.1 Projected Changes in Seasonal Temperature and Precipitation

To explore which climatic variables are driving the projected shifts in bioclimate envelopes, projected mean seasonal temperature and precipitation changes for the four climate scenarios are shown in Figures 3.2 and 3.3 for the 2080s in two subregions. Note that the 1961-90 reference data shows that the North Subregion is distinctly

[5] For further information on stratification of the study area with regard to enduring features and climate, consult the website: www.kootenayresilience.org

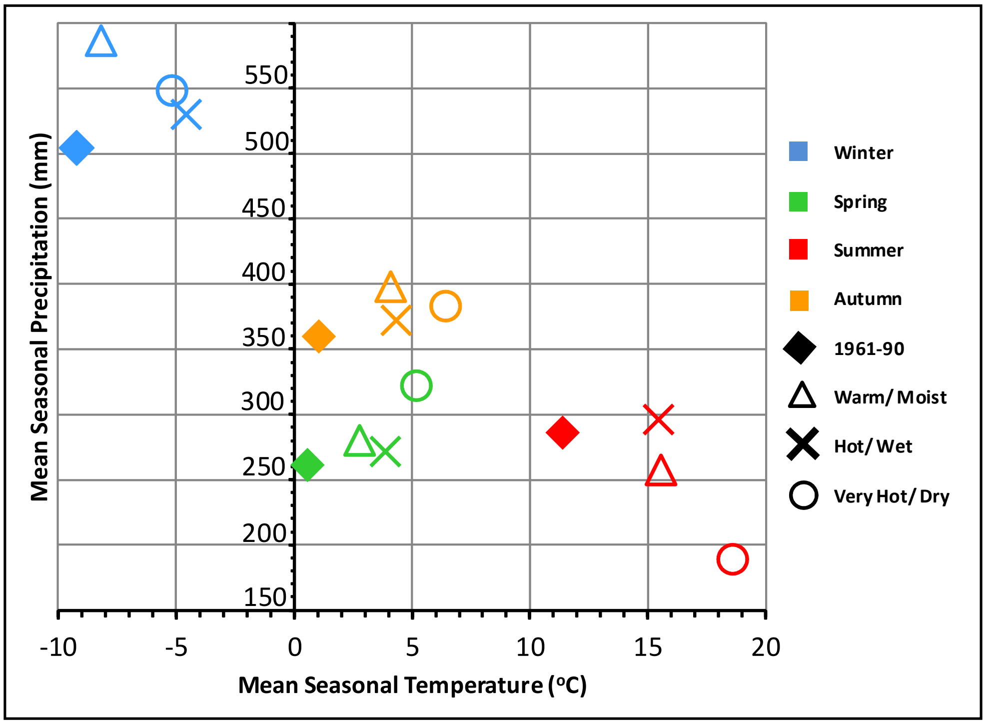


Figure 3.2. Seasonal climate variables for three climate scenarios in the 2080s and the reference period (1961-90) in the North Subregion.

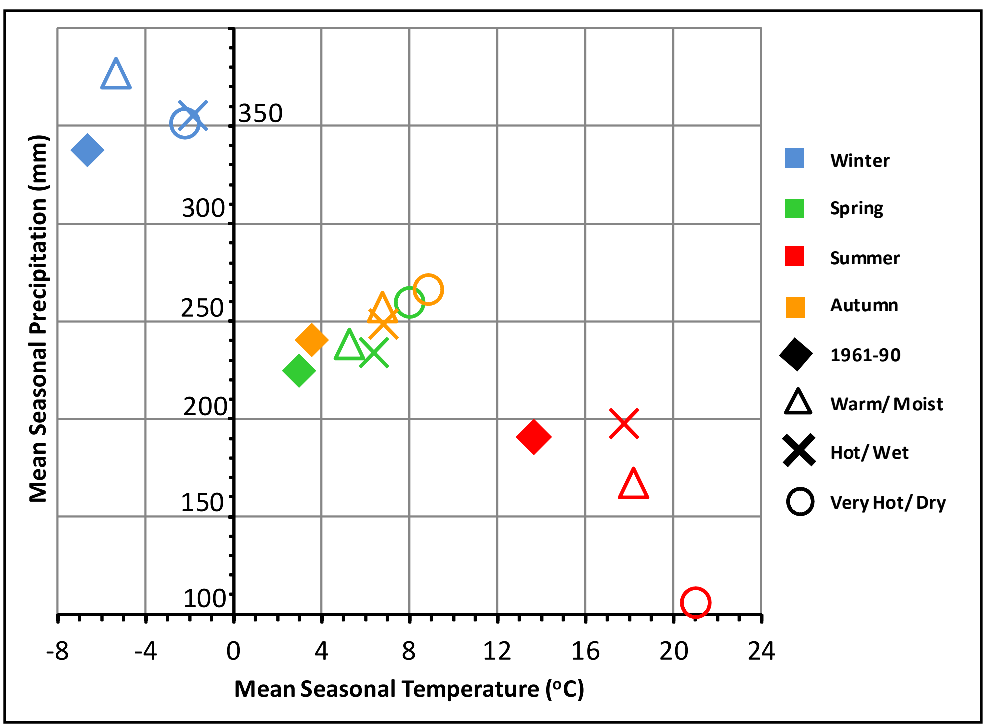


Figure 3.3. Seasonal climate variables for three climate scenarios in the 2080s and the reference period (1991-90) in the South Subregion.

cooler and wetter than the South Subregion. The reference data also show that spring precipitation in the South is greater than summer and similar to autumn, while in the North spring precipitation is less than summer and distinctly drier than autumn. Mid Subregion data (not shown) is intermediate between North and South.

Key Messages:

- All of the scenarios project an increase in temperature for all seasons (movement to the right on the graphs).
- All of the scenarios project increases in winter, spring and autumn precipitation (upward on the graphs) and decreases in summer precipitation (downward on the graphs), except the Hot/ Wet that shows a very slight increase in summer.
- The Very Hot/ Dry scenario is distinct from the other scenarios in its projection for much hotter and drier summers and warmer springs and autumns, remaining within the range of the other models otherwise. The next section will demonstrate that this subtle difference has potentially large consequences.

3.2 Ecosystem Bioclimate Envelope Projections

The reference period (1961-90) locations of the ecosystem climate envelopes that have projected coverages in the study area of more than 50km^2 in one of the three emission scenario combinations are currently found as far south and east as Colorado and Kansas, through BC and north to coastal Alaska, as shown in Figure 3.4. The reference period grassland/steppe, savanna and dry forest bioclimate envelopes from the western US are generally projected for lower elevations in the South subregion all scenarios, and at lower or mid elevations in all subregions in some of the scenarios. The reference period bioclimate envelopes from coastal transition locations are generally projected for upper elevations, mostly in the wetter scenarios. The Alaskan tundra bioclimate envelopes are projected for the highest elevations in selected scenarios.

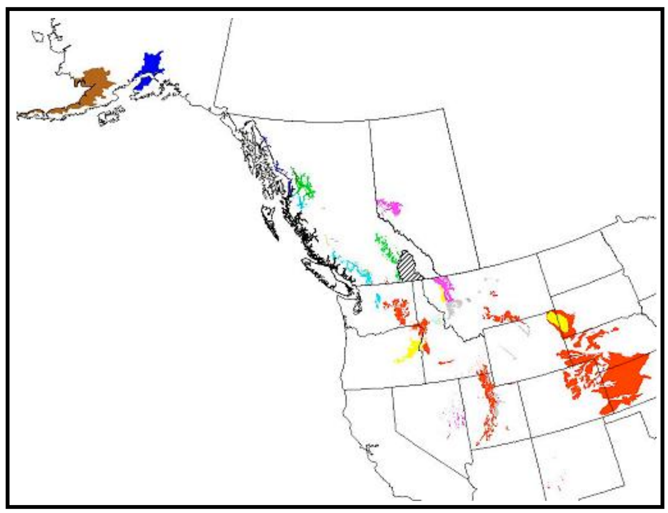


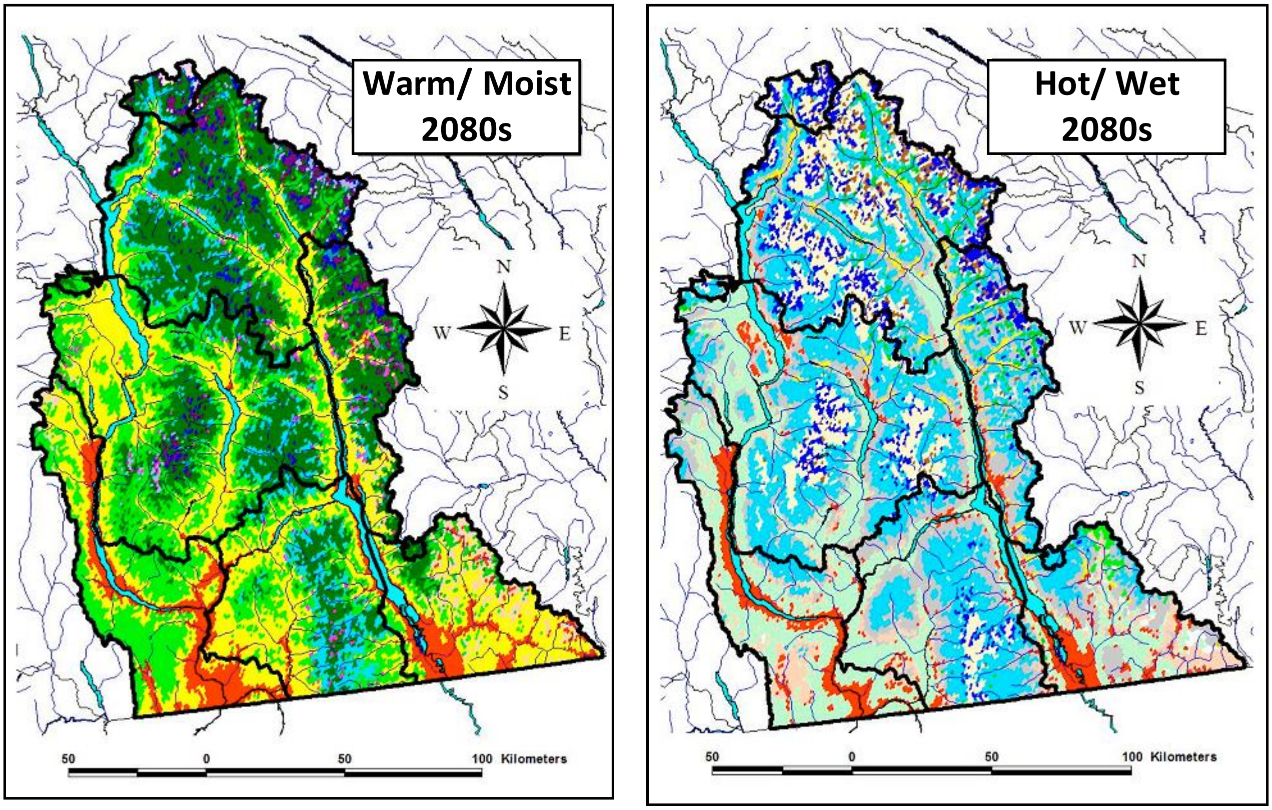
Figure 3.4. Reference period (1961-90) locations of bioclimate envelopes that may occur in the study area in the 2080s based on results from Random-Forest analysis of three climate scenarios. Colours of source areas are consistent with the other figure legends.

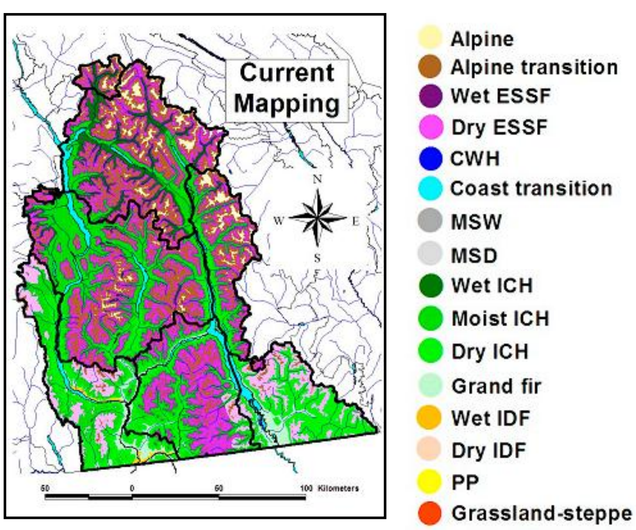
The projected changes in bioclimate envelopes for the study area for the three scenarios in the 2080s are shown in Figures 3.5 – 3.8. All of the scenarios demonstrate significant changes by the 2080s, with variation in results depending on the variation in climatic variables discussed above. Table 3.1 summarizes the projections for the three scenarios by subregion and elevation band.

CAUTION: To assist BC readers envisioning the type of climatic environments that may occur in the future, the climate envelopes have been designated with names of the most similar ecosystems that currently exist in BC. Although these climate envelopes are described with ecosystem names that are familiar, it should not be assumed that the future ecosystems that will develop in these climate envelopes will be identical to ecosystems that readers are familiar with.

Table 3.1. Summary of current and projected bioclimate envelopes by subregion and elevation band.

Assm't Unit	Current Mapping	Climate Scenario		
		Warm/ Moist	Hot/ Wet	Very Hot/ Dry
North <1000m	Moist ICH and Wet ICH	Mainly Ponderosa pine savanna with minor Dry ICH	Mixed grand fir forest and MSD with minor Ponderosa pine savanna	Mainly grassland/ steppe
North 1000-1500m	Moist ICH and Wet ICH with minor Wet ESSF	Mixed Ctran, Dry/ Moist/ Wet ICH, and minor Ponderosa pine savanna	Ctran with MSD, and minor CWH and Moist ICH	Mainly Ponderosa pine savanna
North 1500-2000m	Wet ESSF and Atran	Mainly Wet ICH, with minor Ctran and Moist ICH	Mixed Alpine and Ctran, with CWH and minor MSD and Dry ESSF	Mainly Ponderosa pine savanna, with Dry ICH and minor Dry ESSF and Ctran
North >2000m	Atran and Alp	Mainly Wet ICH with Wet ESSF and minor CWH	Alpine with CWH, Atran and Ctran	Mixed Dry ICH and Wet ICH, with Dry ESSF, Ctran and Ponderosa pine savanna
Mid <1000m	Dry ICH and Moist ICH	Mainly Ponderosa pine savanna with minor grassland/ steppe	Mainly grand fir forest with MSD and grassland/ steppe	Grassland/ steppe
Mid 1000-1500m	Moist ICH and Wet ESSF	Mainly Ponderosa pine savanna with Dry ICH	Mixed MSD, Ctran and grand fir forest	Grassland/ steppe and Ponderosa pine savanna
Mid 1500-2000m	Wet ESSF	Mainly Wet ICH with Dry ICH and Moist ICH, and minor Ctran and Ponderosa pine savanna	Mainly Ctran with MSD, and minor CWH and grand fir forest	Mainly Ponderosa pine savanna
Mid >2000m	Atran and Alp	Mainly wet ICH with minor Wet ESSF and Moist ICH	Mixed Ctran and Alpine, with MSD and CWH	Mixed Ponderosa pine savanna, dry ICH and dry ESSF
South <1000m	Dry ICH and grand fir forest with minor Dry IDF	Mainly grassland/ steppe, with Ponderosa pine savanna	Mixed grand fir forest and grassland/ steppe	Grassland/ steppe
South 1000-1500m	Dry ICH and Moist ICH	Mainly Ponderosa pine savanna with Dry ICH and minor grand fir forests	Mainly grand fir forest with MSD and Dry IDF, with minor grassland/ steppe and Ctran	Mainly grassland/ steppe with minor Ponderosa pine savanna and Wet IDF
South 1500-2000m	Dry ESSF and Wet ESSF	Mainly Dry ICH, with Wet ICH, Ctran, Ponderosa pine savanna and Dry IDF and minor Moist ICH	Mainly Ctran and MSD, with dry IDF and grand fir forest, and minor Dry ESSF and CWH	Mixed Wet IDF and Ponderosa pine savanna, with minor grassland/steppe and Dry ICH
South >2000m	Dry ESSF and Wet ESSF with minor Atran	Mainly Wet ICH, with Moist ICH	Mainly Ctran with alpine	Mixed Dry ICH, Wet IDF and Ponderosa pine savanna





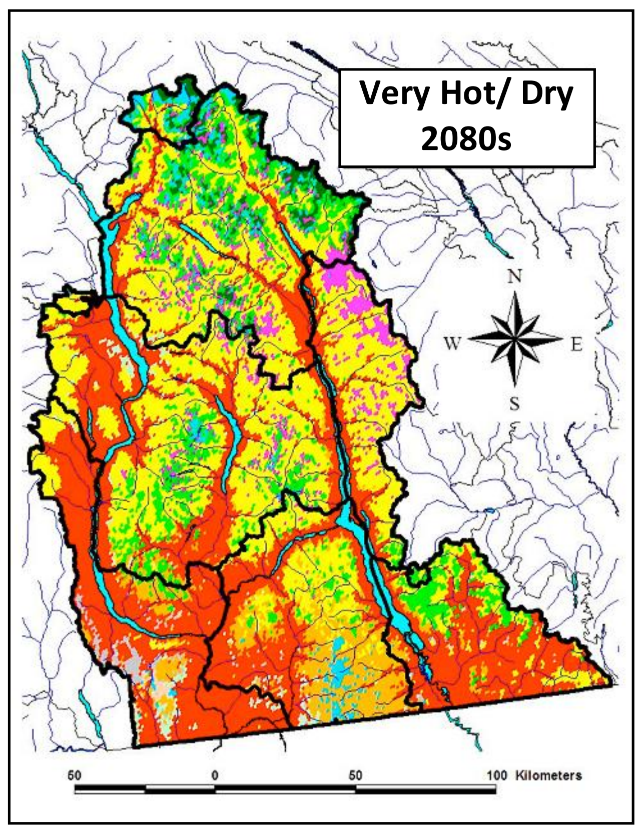
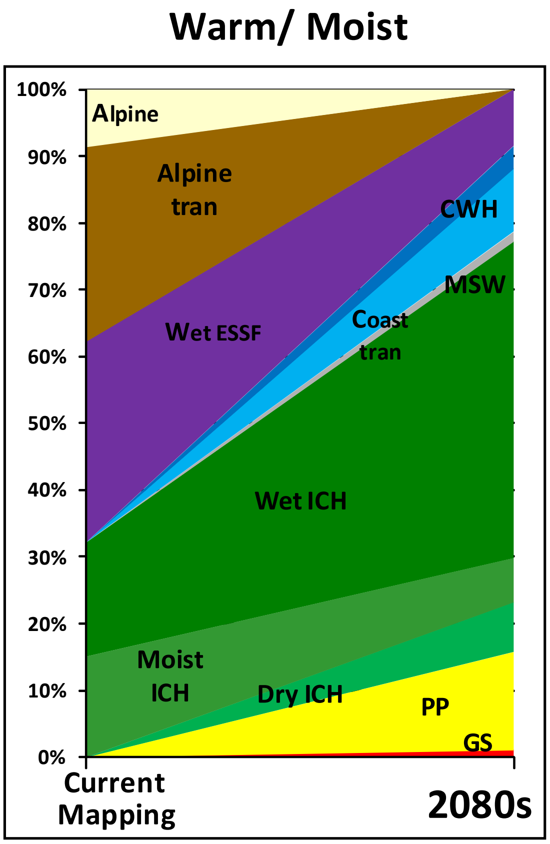
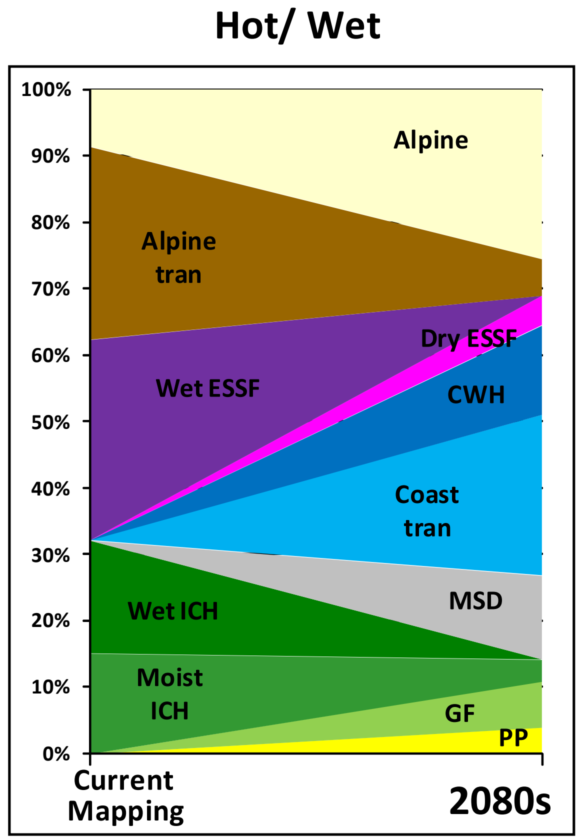


Figure 3.5. Bioclimate envelope shifts projected by three climate scenarios for the 2080s compared to current mapping of generalized ecosystems.





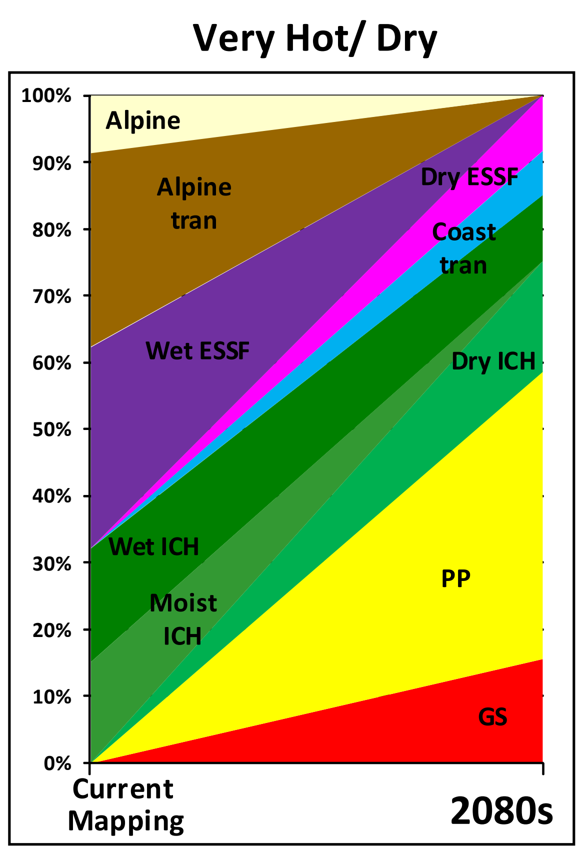
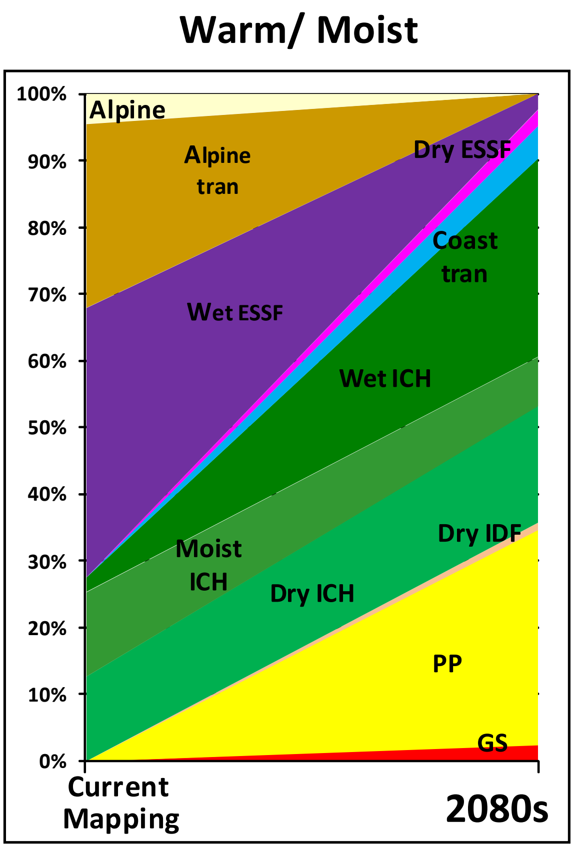
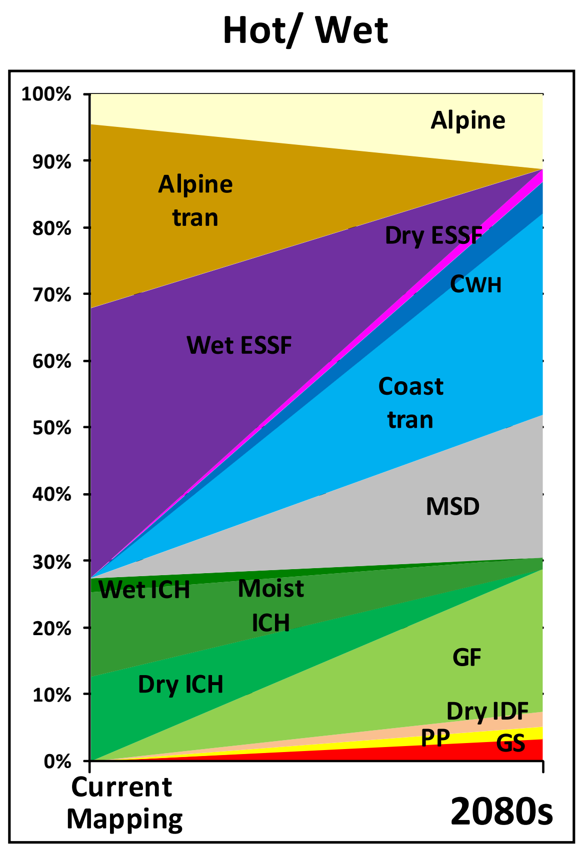


Figure 3.6. Schematic representations of projected bioclimate envelope shifts for the North subregion under three climate scenarios.





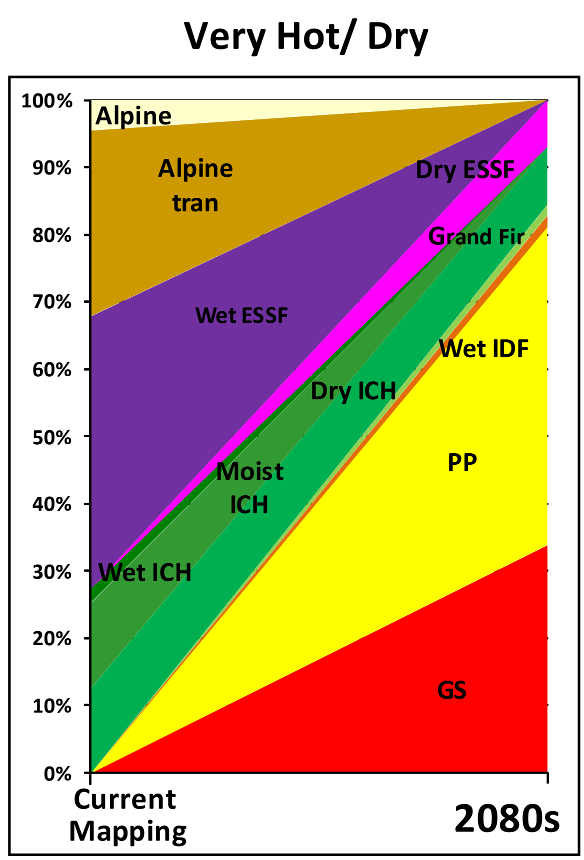
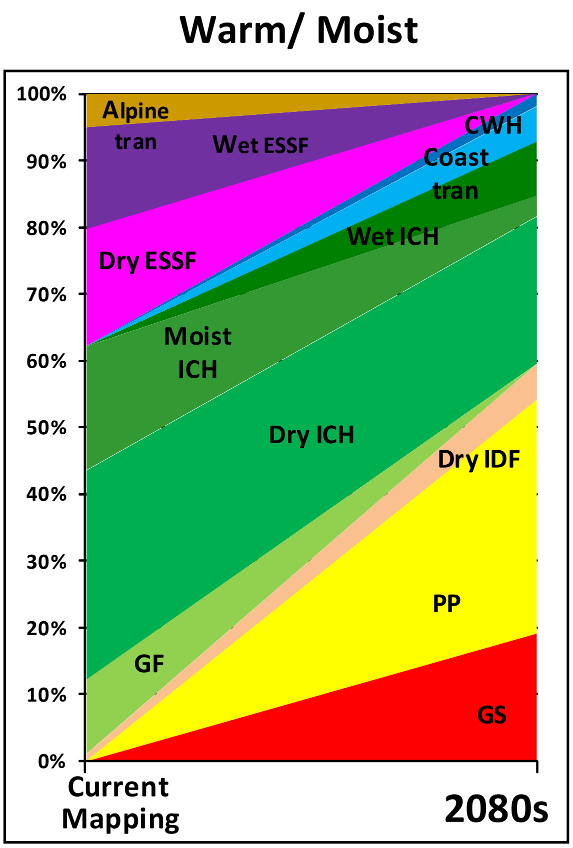
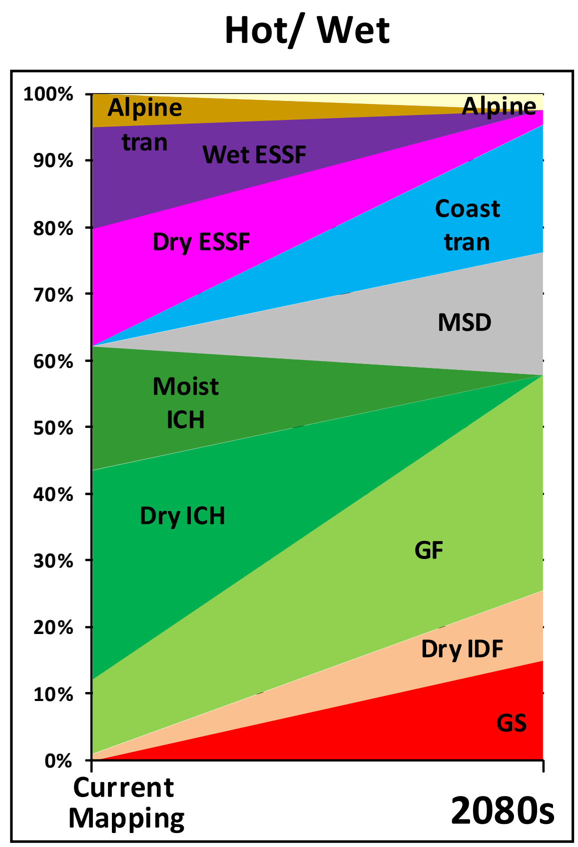


Figure 3.7. Schematic representations of projected bioclimate envelope shifts for the Mid subregion under three climate scenarios.





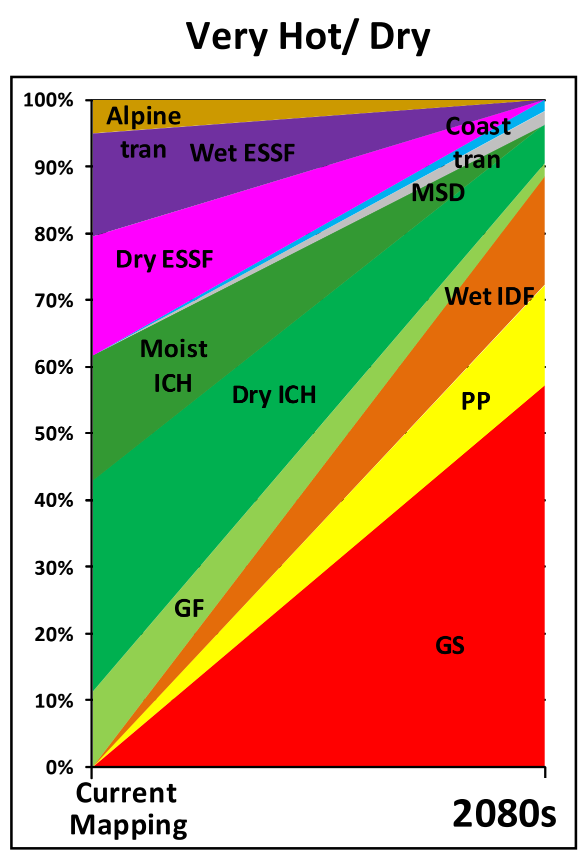


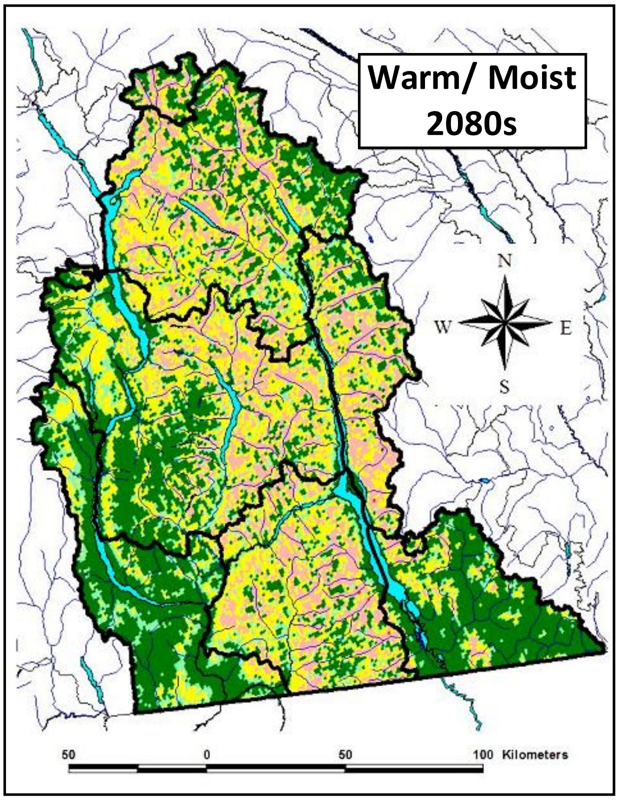
Figure 3.8. Schematic representations of projected bioclimate envelope shifts for the South subregion under three climate scenarios.

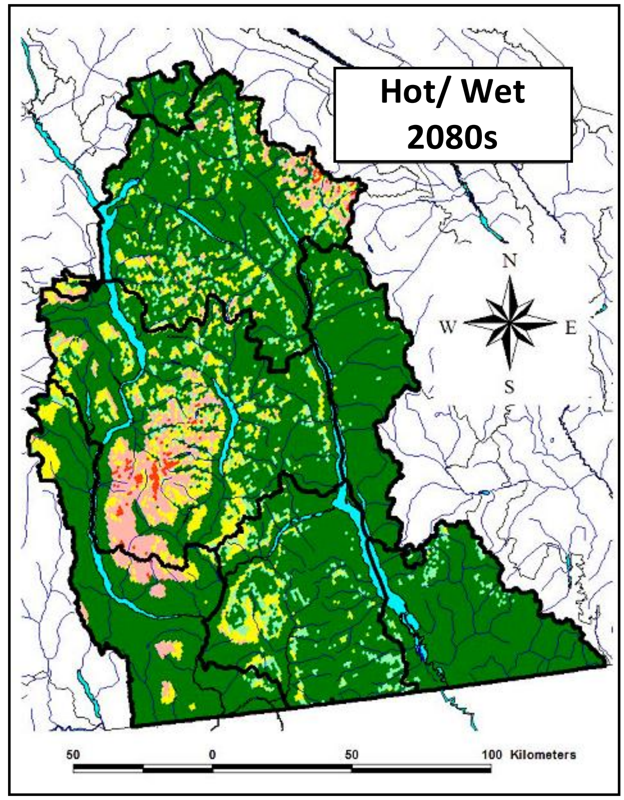
Across all of the study area, all three scenarios project bioclimate envelopes shifts that reflect decreasing moisture availability at mid and lower elevations –differing in magnitude of change, but not direction. At the lowest elevations in the South subregion, all of the scenarios project shifts from ICH bioclimate envelopes to grassland-steppe envelopes. At the upper elevations the results are more variable, with one scenario projecting an upward shift of ICH climate envelopes, another tending to more coastal transition ICH/CWH, and the third showing a shift to semiarid Ponderosa pine savanna envelopes, with very limited moist and coastal transition ICH/CWH envelopes at the highest elevations. All of the scenarios project very large decreases in ESSF and parkland/woodland (Atran) bioclimate envelopes – approaching complete elimination in most cases. Appendix 2 provides higher resolution mapping by subregion of the projected bioclimate envelope shifts.

The schematic representations in Figures 3.6, 3.7 and 3.8 demonstrate the magnitude of shift in bioclimate envelopes by comparing current bioclimate envelope distribution with projected distribution in the 2080s. The graphics are gross simplifications, seeming to present a smooth transition of what will undoubtedly be a complex and erratic process, where changes on the ground will often be linked to random disturbance events (Schneider et al. 2009, Biggs et al. 2009). Appendix 3 also provides a more detailed timeline for another scenario, demonstrating that the projected changes in the bioclimate envelope shifts themselves are non-linear.

3.3 Novel Bioclimate Envelopes

Areas where the projections of future climate envelopes indicate the potential for novel or non-analogue climates, i.e. climatic envelopes that are not currently present in western North America, are shown in Figure 3.9. These areas are projected to be new climatic niches (i.e. new combinations of season climatic variables) that did not exist anywhere in western NA during the reference period (1961-90). One example of the significance of this information is how it impacts the interpretation of the bioclimate projections reported above. Where the Mahalanobis distance is less than one (green in Figure 3.9), the bioclimate projections discussed previously are a good match between projected climate and the ecosystem classification. Where the Mahalanobis distance is greater than one (pink and red in Figure 3.9), there is no match, the ecosystem classification is only the most similar out of the potential options (i.e. the envelopes available in western NA). Hence bioclimate envelope projections in non-analogue situations should be considered less precise than those in analogue situations. Table 3.2 summarizes the projected occurrences of novel bioclimates for the three scenarios.





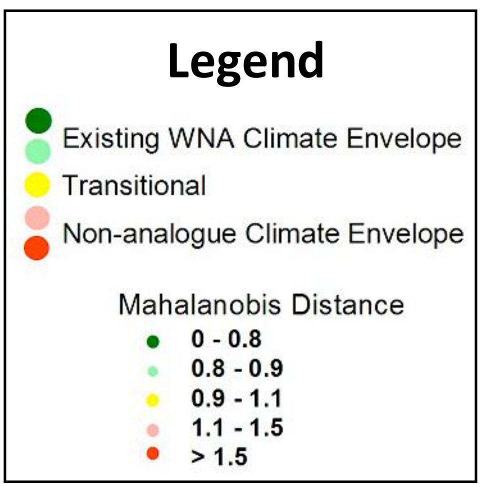


Figure 3.9. Projected occurrence of non-analogue bioclimate envelopes for the three climate scenarios. These represent the potential for occurrence of novel ecosystem climate niches with no present analogues in western North America.

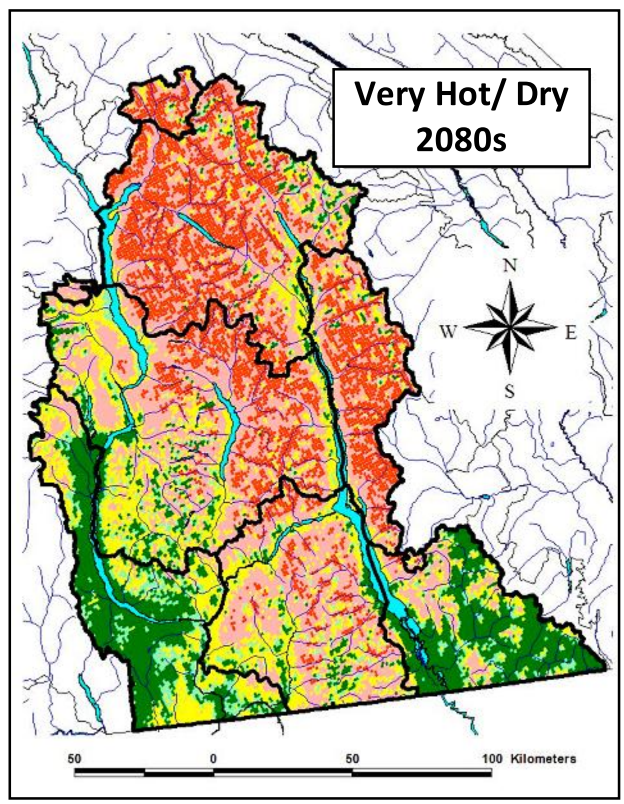


Table 3.2. Distribution of novel bioclimate envelopes by scenario, subregion and elevation band.

Area	Climate Scenario		
	Warm/ Moist	Hot/ Wet	Very Hot/ Dry
North (lower)	Extensive moderately novel envelopes	No novel envelopes	Extensive moderately to strongly novel envelopes
North (upper)	Limited occurrence of slightly novel envelopes	Limited occurrence of slightly to strongly novel envelopes in Purcells	Extensive strongly novel envelopes, except SE corner
Mid (lower)	Extensive moderately novel envelopes in Slocan and Kootenay Lake tributaries; none in Columbia valley	No novel envelopes	Extensive moderately novel envelopes except along the southern Columbia valley
Mid (upper)	Limited occurrence of slightly novel envelopes in the Purcells and Selkirks	Limited occurrence of slightly to very novel envelopes in Valhallas	Extensive strongly novel envelopes in Purcells and Eastern Selkirks; Western Selkirks and Monashees moderately novel
South (lower)	Extensive moderately novel envelopes in tributary valleys of the Selkirk Mountains	No novel envelopes	Slightly to moderately novel envelopes n the Selkirks and Southern Monashees; no novel in the remainder
South (upper)	Limited occurrence of slightly novel envelopes at the highest elevations, mainly in the Selkirks	Limited occurrence of slightly novel envelopes in western Selkirks and Rossland Range	Moderately to strongly novel envelopes in the Selkirks, moderately novel in the Purcells; no novel in the Monashees

3.4 Tree Species Climate Envelope Projections

The results of an assessment for shifts in tree species climate envelopes are presented in Figures 3.10, 3.11, 3.12, 3.13, 3.14, 3.15. The assessment included projections from an ensemble of 18 GCM/emission scenario combinations. The figures display currently mapped frequency occurrences of the tree species in the upper left, and averages of projected frequencies for the species at future time periods in the middle column (based on the projections of bioclimate envelopes). The far right column indicates the level of agreement on presence and absence of the species between the 18 GCM/ emission scenario combinations (dark blue indicates 100% agreement the species is present, red 100% agreement the species is absent).

In general, the climate envelopes for trees are projected to shift upslope and northward as temperatures increase and seasonal precipitation patterns are altered. Consistent with increasing summer temperatures and decreases in summer precipitation, drought tolerant species (e.g., Ponderosa pine and Douglas-fir) tend to increase in occurrence, while those found at upper elevations in cooler environments tend to decrease in frequency (e.g., Engelmann spruce). Less drought tolerant species that occur at lower elevations today (e.g., western redcedar and western hemlock) are projected to decrease in frequency at lower elevations and increase in frequency at upper elevations.

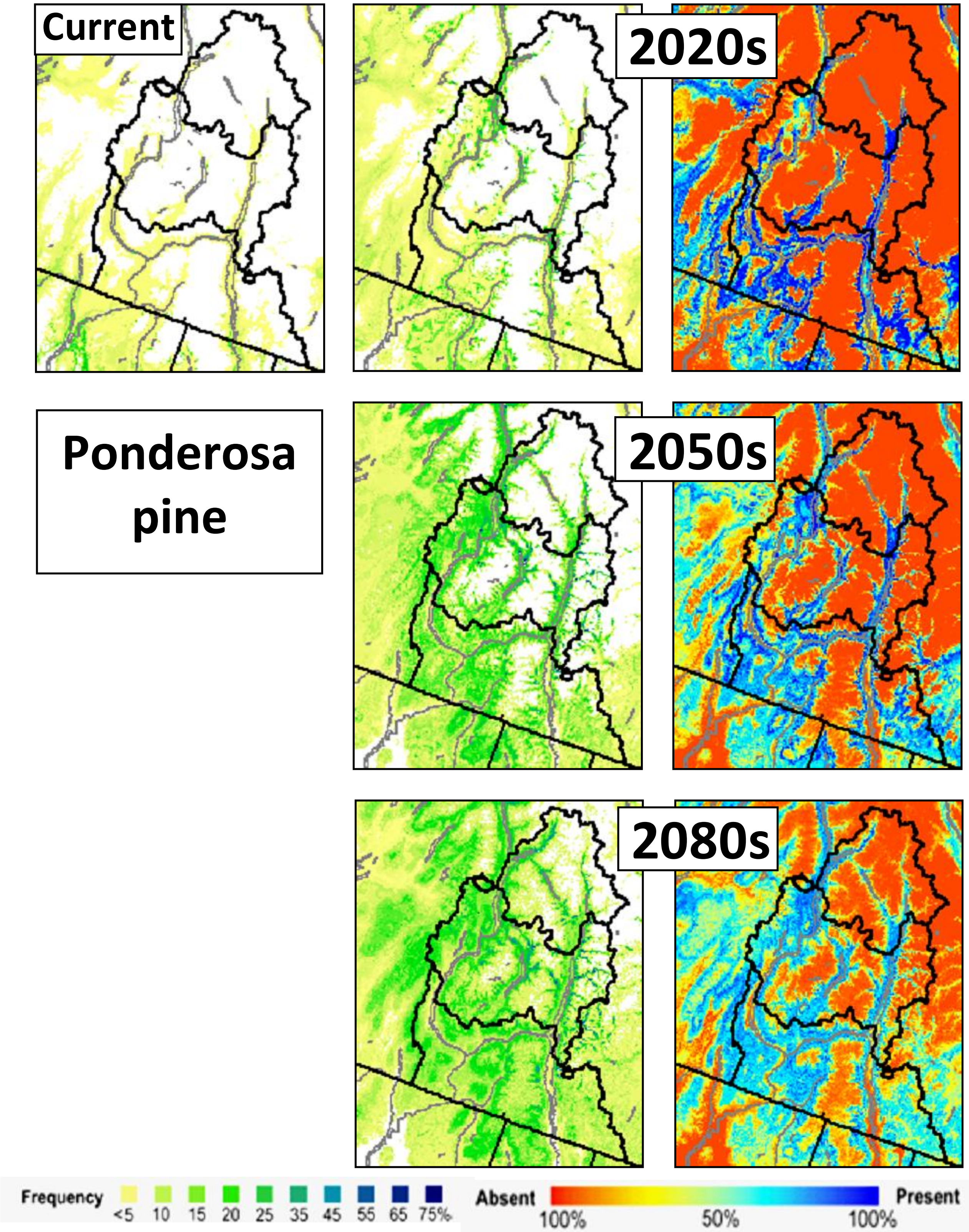


Figure 3.10. Current and projected frequencies for Ponderosa pine. Future estimates are averages of bioclimate envelope shift projections from 18 climate scenarios. The right column shows the presence/ absence agreement between the 18 projections (Gray and Hamann 2011 unpubl. data).

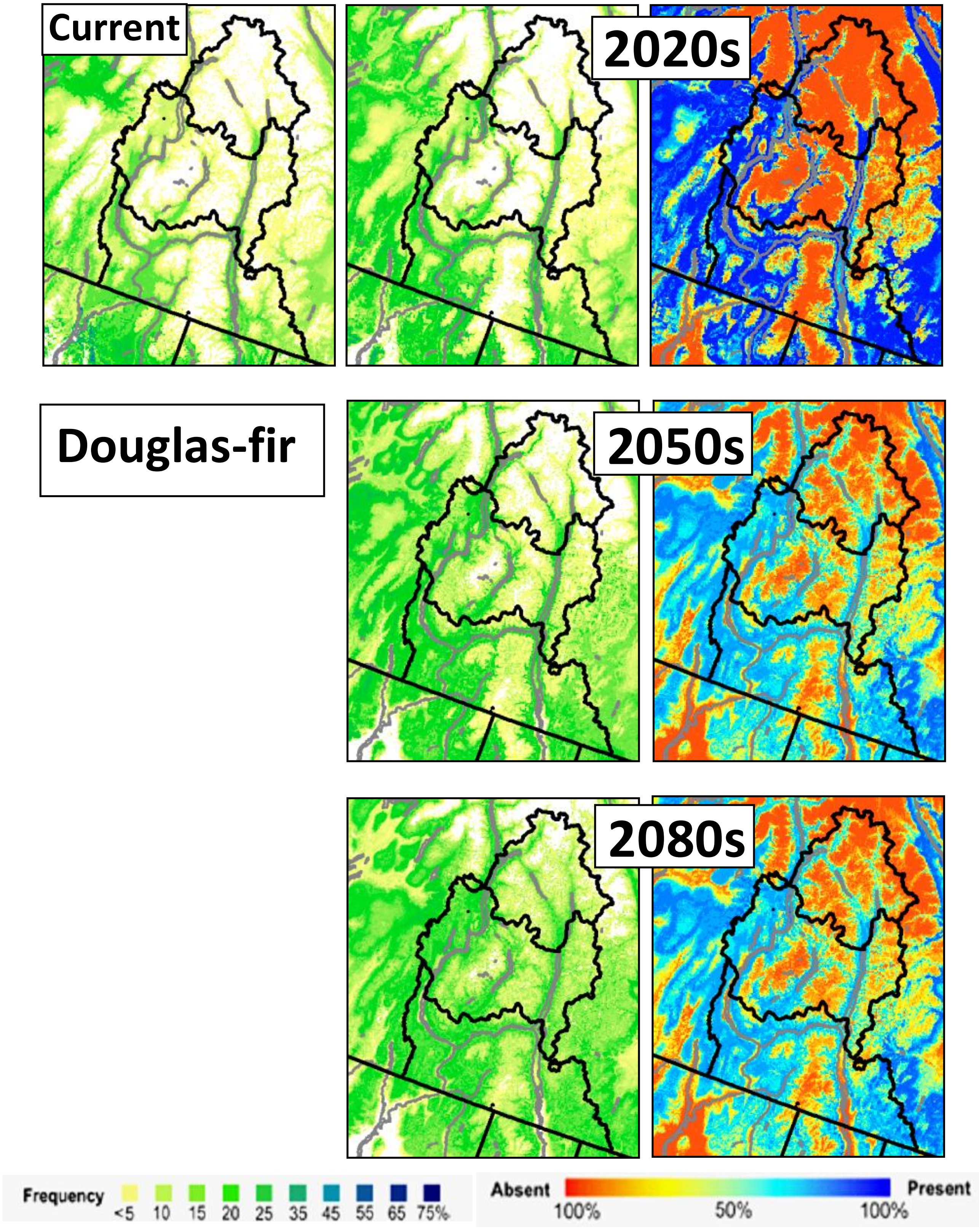


Figure 3.11. Current and projected frequencies for Douglas-fir. Future estimates are averages of bioclimate envelope shift projections from 18 climate scenarios. The right column shows the presence/ absence agreement between the 18 projections (Gray and Hamann 2011 unpubl. data).

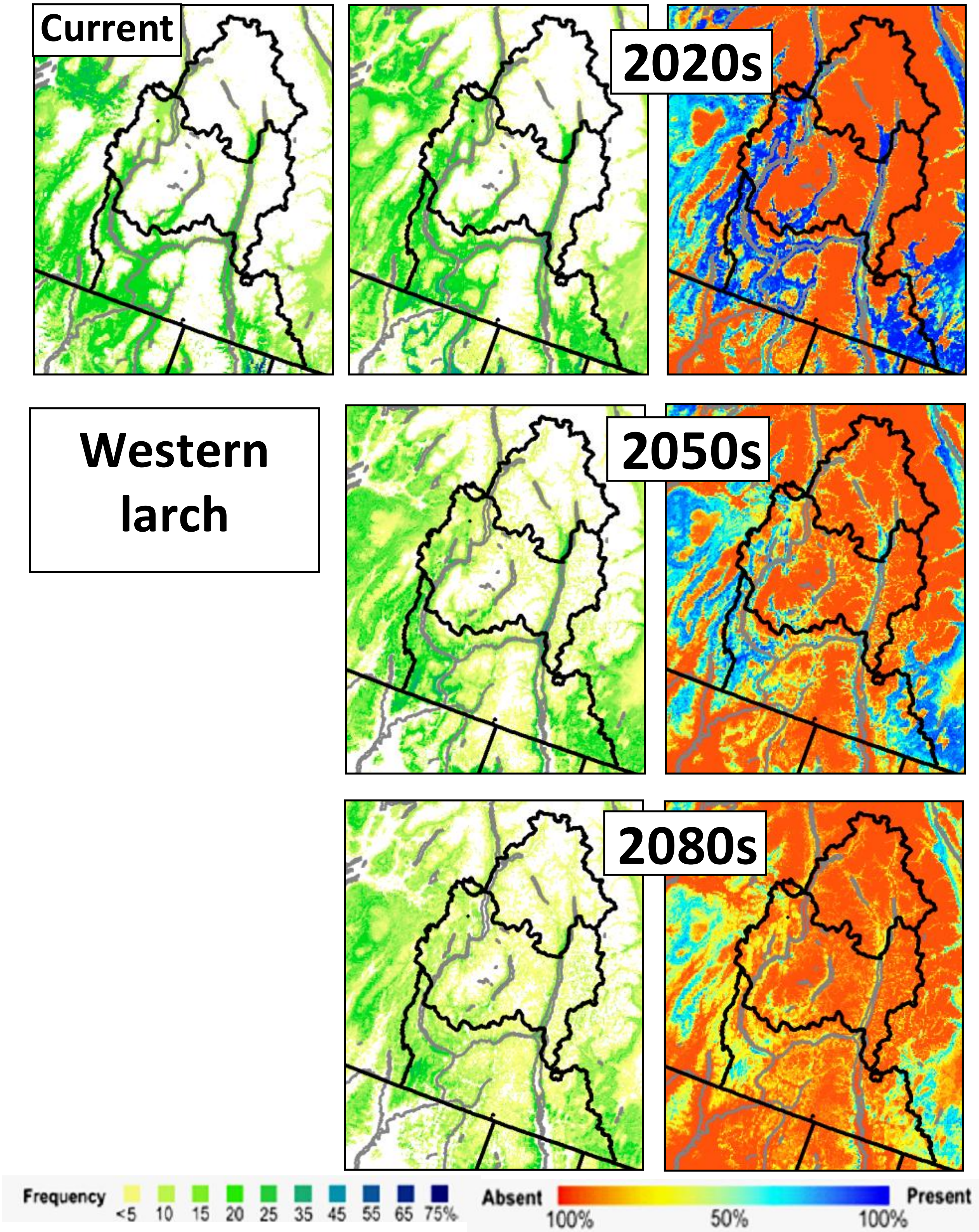


Figure 3.12. Current and projected frequencies for western larch. Future estimates are averages of bioclimate envelope shift projections from 18 climate scenarios. The right column shows the presence/ absence agreement between the 18 projections (Gray and Hamann 2011 unpubl. data).

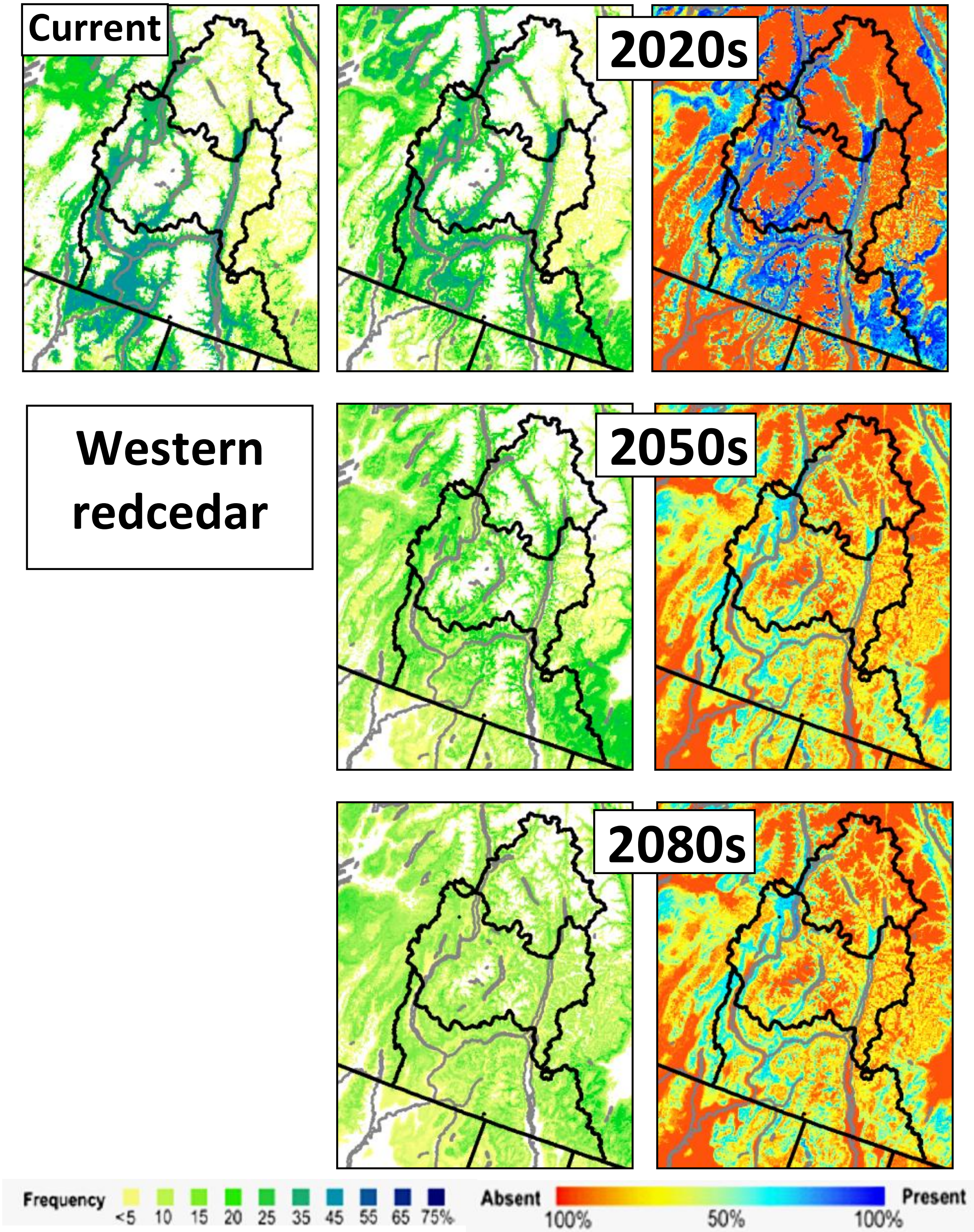


Figure 3.13. Current and projected frequencies for western redcedar. Future estimates are averages of bioclimate envelope shift projections from 18 climate scenarios. The right column shows the presence/ absence agreement between the 18 projections (Gray and Hamann 2011 unpubl. data).

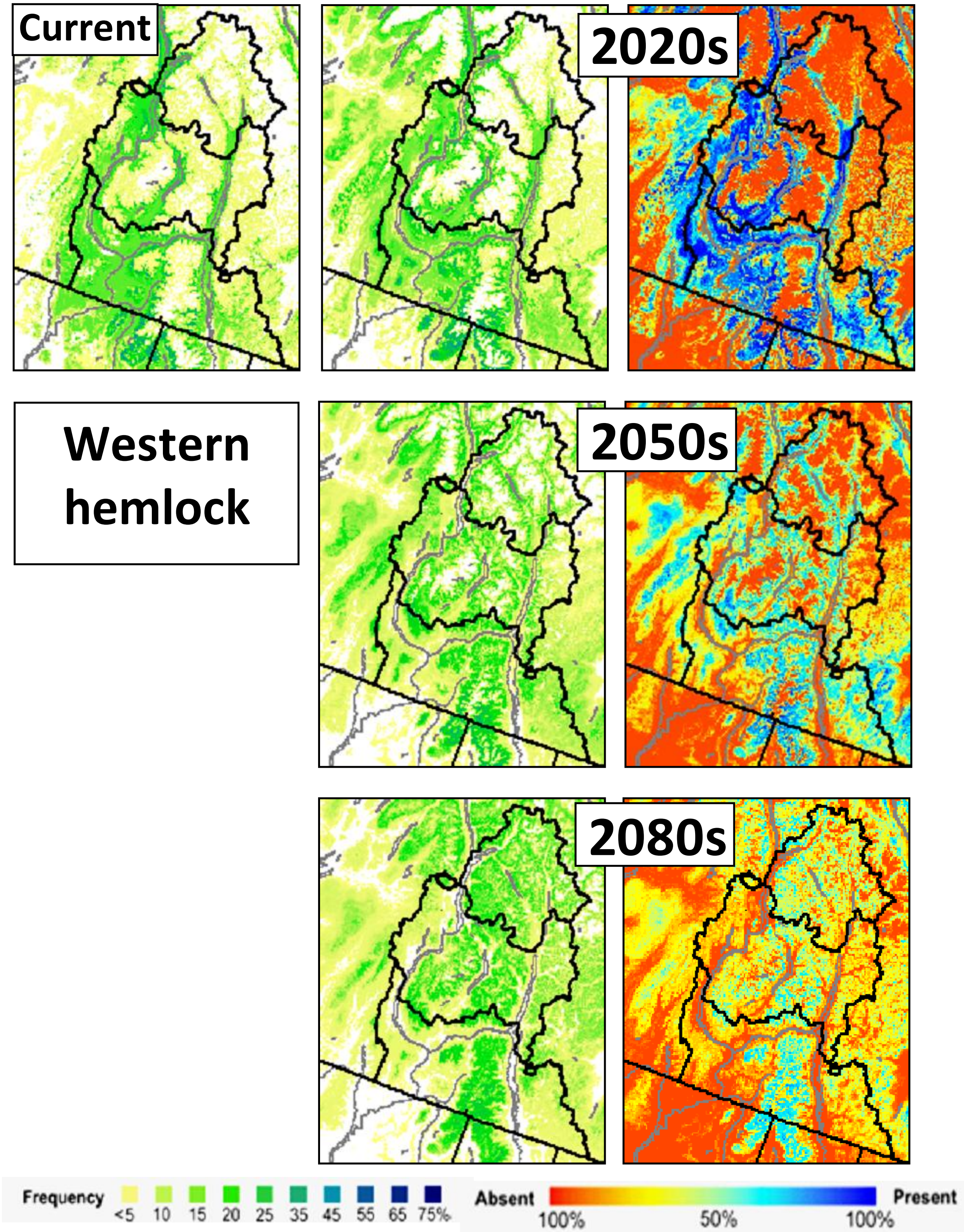


Figure 3.14. Current and projected frequencies for western hemlock. Future estimates are averages of bioclimate envelope shift projections from 18 climate scenarios. The right column shows the presence/ absence agreement between the 18 projections (Gray and Hamann 2011 unpubl. data).

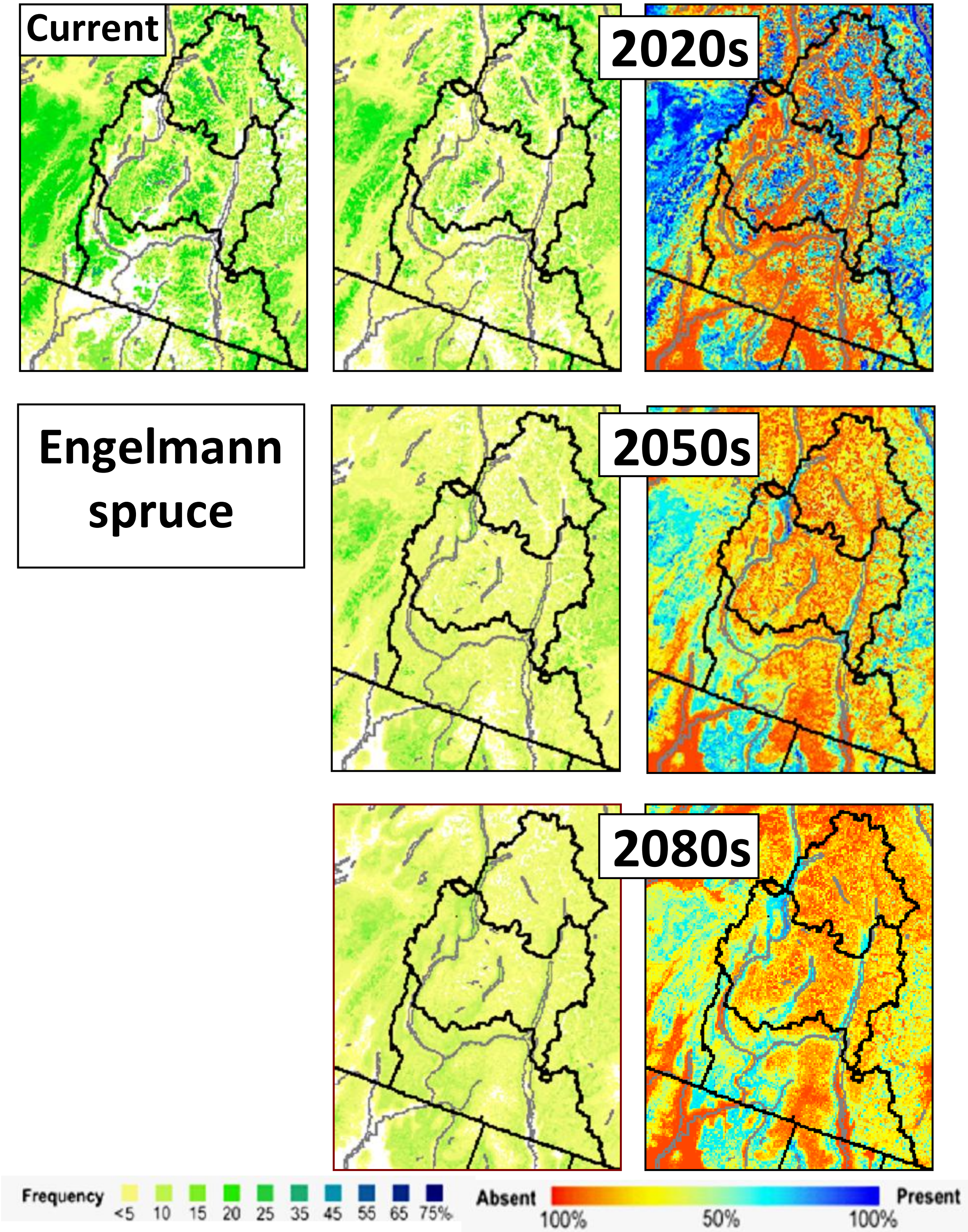


Figure 3.15. Current and projected frequencies for Engelmann spruce. Future estimates are averages of bioclimate envelope shift projections from 18 climate scenarios. The right column shows the presence/ absence agreement between the 18 projections (Gray and Hamann 2011 unpubl. data).

4.0 DISCUSSION

4.1 Ecosystem Changes

The modeling of projected shifts in bioclimate envelopes provides useful information on potential trends in ecosystem changes due to climate change. The comparison of a range of GCM/ emission scenario projections provides one approach to examining the level of uncertainty associated with the range of predictions: for some areas of the region the direction of change is similar across all models and scenarios (e.g. in general for low elevations), where for others (higher elevations), the predicted outcomes differ quite significantly across combinations of models and emission scenarios.

In addition, examination of multivariate Mahalanobis distance measures between projected and existing climatic niches identifies potential occurrences of novel or non-analogue climate envelopes. The location and area of non-analogue climate envelopes varied with GCM/ emission combination, and generally increased with the number of decades projections extended into the future. The relevance of identifying potentially novel climate combinations in future is that we have less predictive power of the type of ecosystem that may be associated with that set of climatic variables, potentially increasing the uncertainty associated with the future vegetation.

The projected shifts in bioclimate envelopes also provide an indication of which ecosystems and which locations are likely to be most vulnerable to the effects of climate change, whether the effects are direct through mechanisms such as drought, or indirect through mechanisms such as changing disturbances regimes[i]. The projected trends of increasing temperatures, increasing drought and likely decreasing summer precipitation appear to be the major drivers in projection by all three scenarios at the lower elevations. Changes at upper elevations are much more uncertain. The Hot/ Wet scenario projects climate envelopes with increasing temperatures and increasing moisture at upper elevations (tending to coast-like conditions), while the Hot/ Dry scenario projects much warmer and drier climate envelopes at all elevations. The Warm/ Moist scenario projections indicate minimal change in precipitation and only moderate warming at upper elevations, although still resulting in ICH environments shifting upslope and the general disappearance of alpine and subalpine ecosystems.

The trends indicated by the projected climate envelopes are consistent with the results of a parallel component of this project that examined the potential changes in annual area burned (Report #4 Utzig et al. 2011). That study projected significantly increasing annual area burned as climate change progresses through the coming decades, although the degree of increase varied with climate scenario. Ecosystems presently occupying the climate envelopes projected for the lower elevations of the study area (e.g. grasslands, steppes and Pondersa pine savannas) typically have frequent low intensity fire regimes. These ecosystems are associated with distinctly shorter fire return intervals and higher annual area burned than the present ICH ecosystems occupying those areas (e.g., NDT 4 vs. NDT 2 and 3).

The change in fire regime also provides a potential mechanism for the catastrophic conversion of present ecosystems to ecosystems more suited to the future climate envelopes. Although projections of climate and bioclimate envelopes provide information on when and where *climate* changes occur, and what equilibrium or *climax* vegetation may eventually develop, the actual changes in ecosystems and species may lag well behind the climate change itself (Schneider et al. 2009). Given that fire is likely be one of the key drivers for those changes, further research on changing fire regimes is needed to fully interpret these results.

Another component of this project has examined the potential for forest insects and other pathogens to increasingly impact ecosystems in the study area (Report #6, Pinnell 2012). Increased temperatures favour population increases in many beetle species. (e.g., spruce beetle, mountain pine beetle – Woods et al. 2010). Drought can reduce the resistance of trees, not only to insects, but also to other pathogens such as root rots, while increasing cool moist conditions can increase the incidence of some rusts, and warm moist conditions favour some foliar diseases (Woods et al. 2010). Although increased drought conditions are projected by all scenarios for lower elevations, particularly in the summer, some of the scenarios do project increased moisture in spring and fall, especially at the upper elevations. Recent outbreaks of Douglas-fir beetle, spruce beetle, mountain pine beetle and birch mortality may be initial indications of future changes. Insects and pathogens will also likely play an important role in future ecosystem shifts, as more vulnerable species fall prey to insects and pathogens, more resilient species survive, and more resistant and better adapted species expand their ranges.

The lower elevation ecosystems of the study area (e.g., ICHdw), especially in the South Subregion, have a wide diversity of tree species, and these offer significant opportunities for local tree species to extend or shift their ranges upslope as climate changes. It is also possible that additional species that are not present in the study area today, but are present where the projected climate envelopes occur today, could expand or shift their ranges to include the study area (e.g., amabilis fir, Sitka spruce, red alder, burr oak). However the distances involved, species dispersal capabilities, and the rate of climate change may limit such opportunities. Although all of the projected bioclimate envelopes are dominated by tree species that already occur within the study area, it is likely that the genotypes of trees in the current locations of those envelopes, are distinct from those currently occurring in the study area. Therefore, even though a species may be locally present, there still will be a need for significant genetic variation in local populations, and adaptive evolutionary for that species to maintain fitness as climate changes (Gray et al. 2011). The rate of climate change will also be a key factor in determining whether evolutionary adaptation will be successful. Assisted migration may be required in some cases.

4.2 Bioclimate Envelope Analysis – Considerations on Approach and Interpretation

It cannot be over-emphasized that the results presented here are a few of many possible futures. Bioclimate envelope projections have numerous sources of uncertainty, including the choice of modeling technique (e.g., Mbogga et al. 2010, Diniz-Filho et al. 2009, Pearson et al. 2006). As shown in Figures 3.3, 3,4 and 3.5, the choice of GCM, as well as assumptions about future greenhouse gas emissions can significantly affect the predicted outcomes from an analysis. Other studies have also found these variables to be major contributors to uncertainty (e.g., Mbogga et al. 2010, Diniz-Filho et al. 2009).

Some projects have attempted to overcome the complexity of uncertainty by utilizing ensembles of GCM/ emission scenario combinations (e.g. Wang et al. 2012, Diniz-Filho et al. 2009, Gray et al. 2011). The tree species projection component of this report utilized this approach (see Section 3.2). An ensemble approach provides a single “average” outcome, which is easy to comprehend, but it tends to de-emphasize the inherent uncertainty packaged within the results. Although this approach can be accompanied by information on the level of agreement between the individual ensemble projections to provide some indication of uncertainty (e.g., Gray et al. 2011, Wang et al. 2012), it is a potential problem that users tend to place confidence in the “average” outcome in general, when only the results from near 100% agreement between the scenario combinations should inspire confidence. From an adaptation perspective, the ensemble approach provides little or no information about the range of possible outcomes, and therefore encourages users to plan for a single outcome, rather then explore the need for “robust” solutions that may be able to cope with a range of possible outcomes.

Another important source of uncertainty is the degree of similarity between projected climate envelopes, and their contemporary analogues. A recent bioclimate envelope analysis for British Columbia (Wang et al. 2012) has restricted its source area for climate envelopes in the analysis to the province itself, in contrast to our analysis that utilized the full range of bioclimate envelopes across western North America. As expected, the resulting bioclimate envelopes projected for the study area vary from what is projected in our results. In particular, the results presented here, especially for the 2080s show that a significant portion of the study area is projected to become more consistent with climate envelopes that presently occur outside of BC (see Fig 3.2).

The Mahalanobis distance analysis offers one method to assess the degree of similarity between the future projected climates, and the bioclimate envelopes selected by RandomForest. Even with our broader pool of bioclimate envelopes, some of the climate envelopes projected by some climate scenarios for the 2080s were shown to not have current analogues anywhere in Western NA (see Fig. 3.9). Other authors have noted the need to use caution when interpreting the results of bioclimate envelope analysis where the range of potential bioclimate envelopes has been too limited (Czúcz et al. 2009). The potential shift in bioclimate envelopes can be severely underestimated in such studies.

The level of generalization and scale of analysis are also key factors to consider. In a study of projected climate envelopes in northern Britain, Trivedi et al. (2008) demonstrated that the scale and resolution of analysis units was important to recognizing the projected presence of bioclimate envelopes, especially in mountainous terrain. In their study of 10 species, coarse scale analysis projected that climate niches for 9 out of 10 species would persist under 2 contrasting climate scenarios. The fine scale analysis projected that only 2 or 3 would persist, depending on the intensity of the climate scenario. Use of broad scale ecological classification units such as BEC zones compounds this issue. For example, if investigating the potential future distribution of tree species in BC, BEC subzones or subzone variants are consistent with tree species distribution, while BEC zones are too broad. Use of zones as the assessment unit will tend to under-estimate the potential change in habitat availability, as the climate space will be much broader than species that only occur in a portion of the zone (e.g., Wang et al. 2012). In the results presented here, the BEC subzone and seed zones utilized for BC and Alberta define fairly narrow and homogenous climate envelopes, however the ecosystems used to define envelopes for Alaska and the Yukon are quite broad. The US Level IV ecoregions are variable – some are fairly narrow, while others are landscape-based and may include a wide range of elevations. This may potentially create a bias in the analysis, where broader envelopes potentially have a higher likelihood of being selected.

It should be noted that the choice of GCM appears to be a significantly larger driver of the outcome than the assumptions of GHG emissions. The projected increases in temperature (especially summer), and the resulting projected changes in bioclimate envelopes, are much more severe with the HadGEM_A1B scenario, than under the CGCM3_A2 scenario, even though the A1B emission scenario assumes much lower GHG emissions. Also note the fairly minor differences between CGCM3_A2 and CGCM2_A1FI, even though the A1FI emissions assumptions are significantly higher than those for A2 (see App. 3).

Regardless of the limitations, an analysis of projected bioclimate envelope shifts provides a useful tool for assessing the potential magnitude and complexity of climate change impacts on ecosystems. Knowing the current locations of projected bioclimate envelopes allows managers to investigate ecosystems that presently inhabit those environments, and hopefully garner insights on the functioning of those ecosystems, thereby providing information useful for planning local adaptation measures. When combined with information on adaptive capacity, sensitivity and non-climatic stressors, this information is one of the key components to any broad-based ecological climate change vulnerability assessment.

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APPENDIX 1: ADDITIONAL INFORMATION ON METHODS

Bioclimate Projections

Ecosystem climate envelope projections were based on an assessment of climate vs. ecosystem distribution. To establish current climate variables, the Hamann group acquired monthly climate data for western North America (west of 100^{o} W long.) for the 1961-90 period from ClimateWNA[6] (Hamann and Wang 2005, Mbogga et al. 2009, Wang et al. 2012). The data was assigned to a 1 km grid for the western NA study area (approx. 10 million points). Ten of the least inter-correlated and biologically-relevant variables were chosen for the analysis:

- mean annual temperature
- mean temperature of the warmest month
- mean temperature of the coldest month
- continentality (difference between mean January and July temperatures)
- mean annual precipitation
- growing season precipitation (May to September)
- number of frostfree days
- number of growing degree days above 5°C
- annual climate moisture index (Hogg 1997)
- summer climate moisture index (Hogg 1997)

To combine the climate data and ecosystem classification units, classification tree analysis was employed. The RandomForest modeling tool was utilized (Breiman, 2001). RandomForest has previously demonstrated utility in bioclimate assessments (Lawler et al. 2006, Rehfeldt et al. 2006). RandomForest builds multiple classification trees from bootstrap samples of the training data, and then selects the most appropriate ecosystem type by majority vote over all classification trees. To build the classification trees, 100 grid cells were randomly chosen from each of the 770 mapped classification units, and characterized for each of the 10 climate variables for the 1961-90 climate data. This data was used as “training data” for the classification tree analysis software to establish climatic profiles for each ecosystem unit.

Due to the lack of a universal ecosystem classification system for western North America, various classifications were combined to generate coverage for the whole area, resulting in 770 mapped ecosystem classes. The seven primary classification sources by region include:

- Alaska – Ecosystems of Alaska (Joint Federal-State Land Use Planning Commission for Alaska, 1991),
- Yukon, NW Territories, Sask. and W. Manitoba – National Ecological Framework (Govt. of Canada, 1999),
- British Columbia – Biogeoclimatic Ecosystem Classification System of British Columbia Version 4 (Meidinger and Pojar 1991),
- Alberta - Natural Regions and Subregions of Alberta and Seedzones of Alberta (Alberta NRC 2006 and Alberta SRD 2009),
- California and Arizona - Potential Natural Vegetation Maps for CA and AZ (Kuchler, 1993, 1996),
- Other western US states – Level IV Ecoregions of the Continental US (Omernik, 2003, EPA 2007), and,
- BC and Alaska alpine – Alpine Tundra, Barren/Rock, and Glacier/Ice classes based on 30 m resolution remotely sensed landcover data for the US (Homer et al., 2007) and Canada (Wulder et al., 2008).

[6] Available at: http://www.ales2.ualberta.ca/RR/people/hamann/data.html and http://www.genetics.forestry.ubc.ca/cfcg/climate-models.html

Non-Analogue Bioclimates

Mahalanobis distance is a normalized Euclidean distance in multi-dimensional space between the two climate variable combinations (Mahalanobis 1936). Mahalanobis distances between the projected climate, and the average climate envelope for each current ecosystem type (all 770), were calculated for each grid cell, for each climate scenario, and each future time period. The minimum distance was then identified for each grid cell for each scenario.

Figure A2.1 provides a simplified two-dimensional representation of two potential outcomes – one where the grid point is within the climate envelope ("o", MD 0.4), and another where it is close to the climate envelope ("x", MD 1.5), but not actually within it. In the second case, RandomForest could have designated either of the two climate envelopes portrayed, based on the outcome of numerous classification keys as the envelope with the best fit. However, the grid point did not actually fall within either envelope. The Mahalanobis distance reported in this study is to the closest bioclimate envelope, the one chosen be RandomForest could be even greater. For this reason one should use care when interpreting bioclimate envelopes projected by RandomForest without this kind of additional assessment.

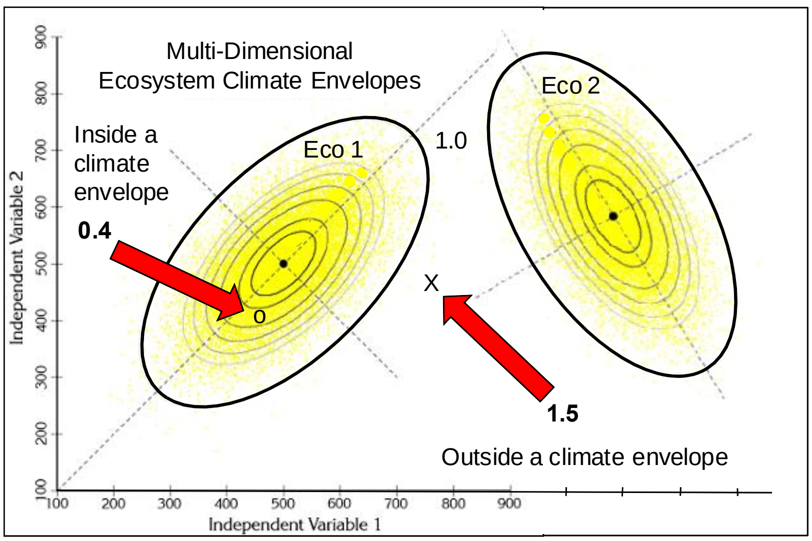


Figure A1.1. Schematic representation of Mahalanobis distance calculations (adapted from: www.jennessent.com/arcview/mahalanobis_description.htm).

APPENDIX 2: BIOCLIMATE ENVELOPE PROJECTIONS BY SUBREGION

The maps in Figures A2.1, A2.2 and A2.3 provide a higher resolution comparison the four climate scenarios presented by subregion (see Appendix 3 for information on CGCM2_A2). Portions of the information presented here is also presented in Figure 3.3 and Appendix 3, at different scales and in differing contexts.

CAUTION: To assist BC readers envisioning the type of climatic environments that may occur in the future, the climate envelopes have been designated with names of the most similar ecosystems that currently exist in BC. Although these climate envelopes are described with ecosystem names that are familiar, it should not be assumed that the future ecosystems that will develop in these climate envelopes will be identical to ecosystems that readers are familiar with.

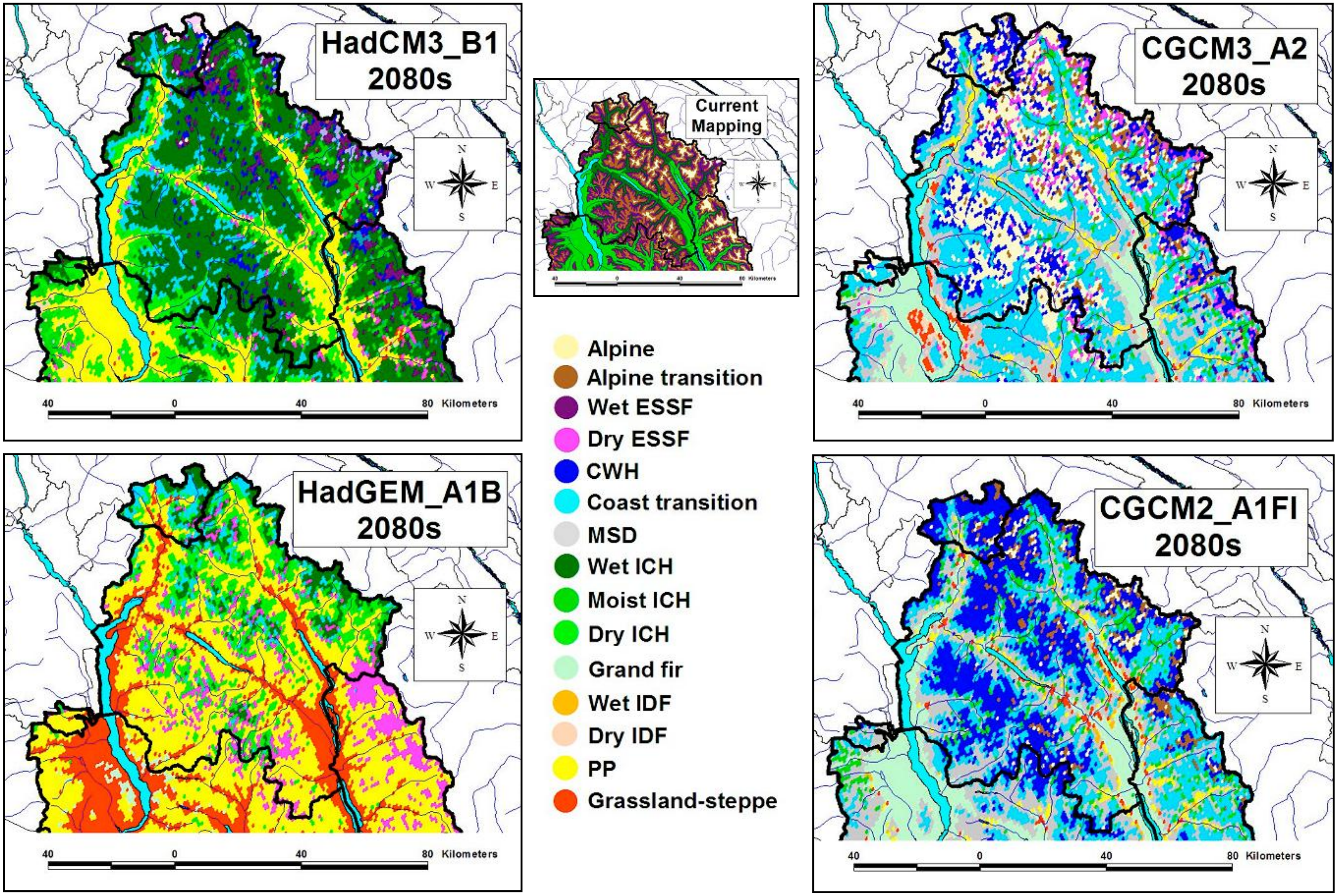


Figure A2.1. Projected shifts in bioclimate envelopes in the North Subregion for four GCM/ emission scenario combinations; modeled with RandomForest and derived from various ecosystem classifications across western North America (Roberts and Hamann 2011, upubl. data).

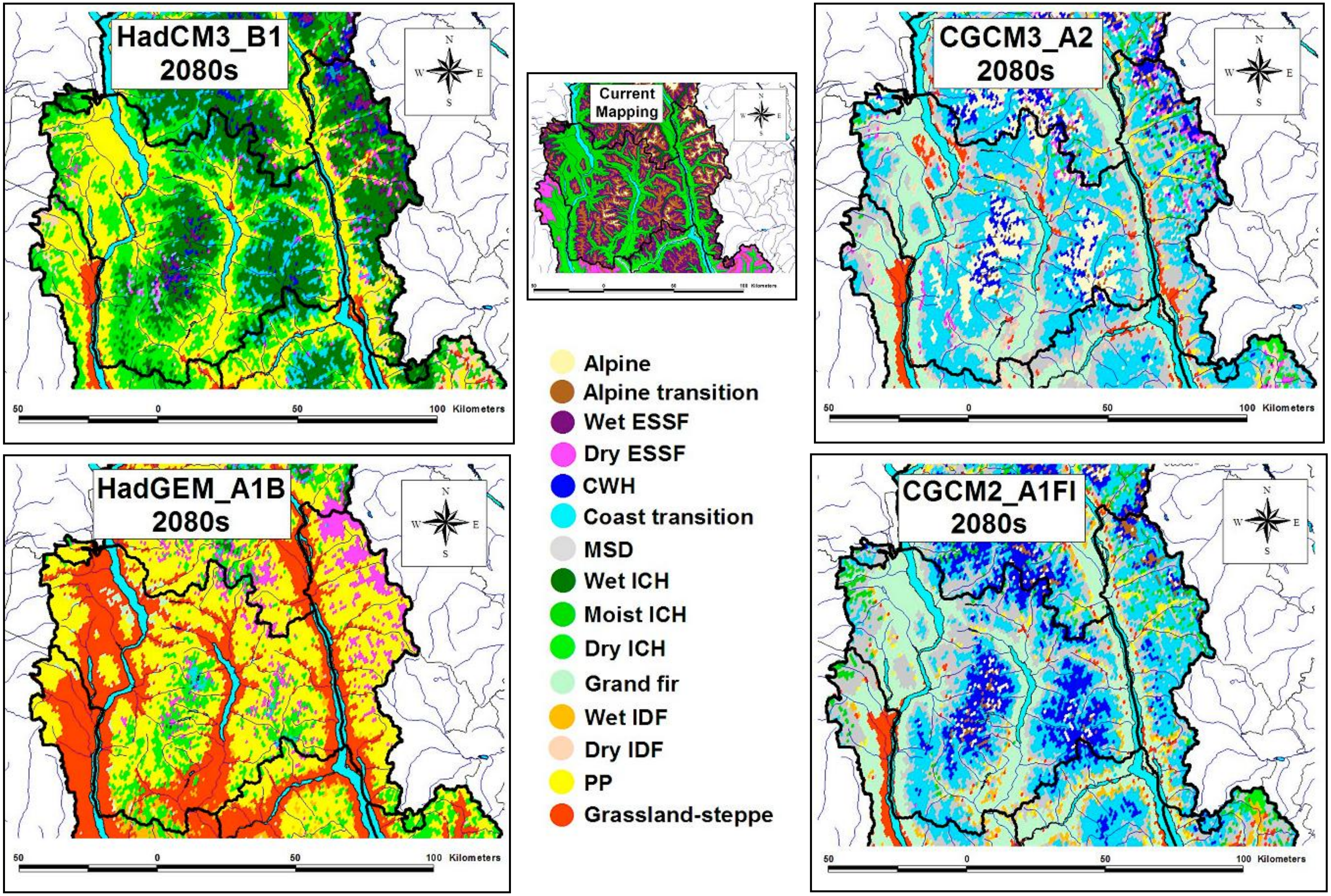


Figure A2.2. Projected shifts in bioclimate envelopes in the Mid Subregion for four GCM/ emission scenario combinations; modeled with RandomForest and derived from various ecosystem classifications across western North America (Roberts and Hamann 2011, upubl. data).

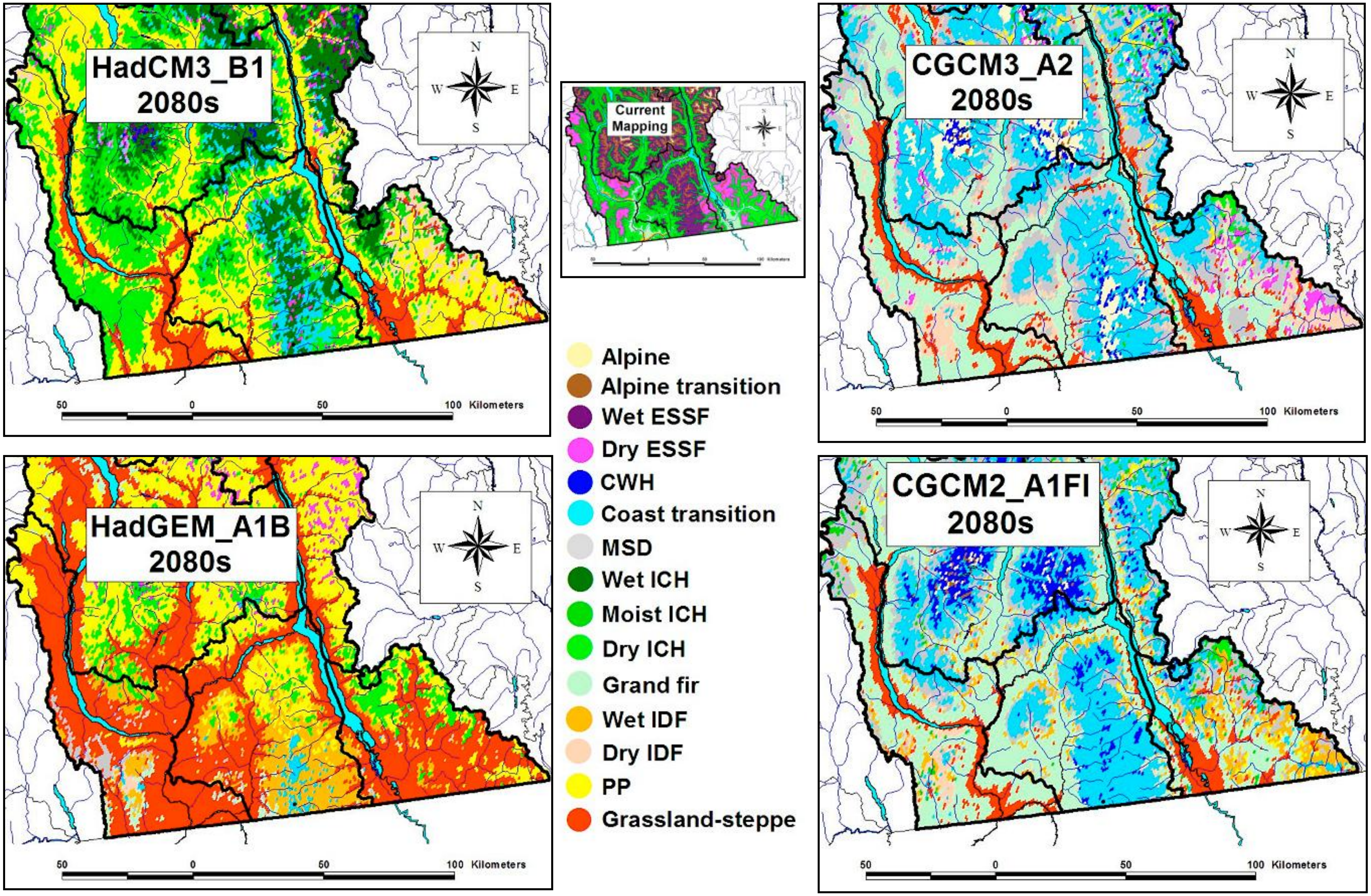


Figure A2.3. Projected shifts in bioclimate envelopes in the South Subregion for four GCM/ emission scenario combinations; modeled with RandomForest and derived from various ecosystem classifications across western North America (Roberts and Hamann 2011, upubl. data).

APPENDIX 3: BIOCLIMATE ENVELOPE PROJECTIONS FOR CGCM2_A1FI

This appendix provides an example of a more detailed assessment of one climate scenario – CGCM2_A1FI_r1. This scenario was selected because it represents the emission trend that is most similar to the one presently being pursued by the world. Although there are limited outputs available for this emission scenario, by selecting one from the Canadian model, it allows for comparison between two emission scenarios with the same model.

CAUTION: Although this climate scenario is explored in more detail, it should not be assumed to be any more likely than the other scenarios. The results of this scenario should always be considered in conjunction with the other three scenarios in the main report. In relation to the other scenarios, this scenario represents a second example of a Hot/ Wet scenario.

To provide a context relative to the other scenarios, Figures A3.1 and A3.2 provide a summary of seasonal climate data that includes all four scenarios. The bioclimate envelope results for this scenario are presented spatially for current mapping of the generalized ecosystems, and projected shifts in envelopes, at three future time periods (2020s, 2050s, 2080s), for each of the three subregions of the study area (North, Mid, South) in Figures A3.3, A3.4. and A3.5. Time sequences of projected ecosystem climate envelope shifts for the scenario, by four elevation bands, for each of the three climatic subregions are shown in Figures A3.6, A3.7 and A3.8. These results are also summarized by subregion, elevation band and time period in Table A3.1. The potential occurrences of novel bioclimates are shown in Figure A3.9.

Projections of climate envelopes from the CGCM2_A1FI scenario for the lower and mid elevations of the study area correspond to climate envelopes that presently occur south of the study area, covering a wide swath across the western US. This is consistent with the projected increases in temperatures in all seasons, and the potential decreases in summer precipitation. In contrast, climate envelopes from that scenario that are projected to occur in the upper elevations are more similar to climate envelopes that presently occur west and northwest of the study area in the coast mountains of BC and southern Alaska. These are consistent with the projected increases in temperature accompanied by likely increases in winter precipitation and increased snow depths. According to this scenario, increased temperatures and summer drought appear to be the key factor at lower elevations, while increased temperatures, a shorter winter season, and greater snow depths may be key factors at upper elevations. The more detailed time sequences in Figures A3.6 - A3.8 demonstrate that the projected changes are not likely to develop in a smooth linear fashion.

Although this scenario, as well as the other three scenarios show similar trends toward warmer and more drought-prone climate envelopes for the lower elevations, at the upper elevations, the two Canadian model scenarios (CGCM) tend to show a trend to warmer and wetter climate envelopes, with the A1FI scenario showing more extensive loss of alpine conditions at the highest elevations and increased occurrences of more coastal climate envelopes. This scenario is similar to the CGCM3_A2 scenario, having been generated by the same GCM, however the A1FI emission scenario results in a more rapid increase in CO_2 emissions. Based on emission rates, the outcomes from the A2 scenario in the 2020s would likely be similar to the A1FI scenario in the 2080s.

The result of analysis for novel bioclimate envelopes for this scenario at two time periods are presented in Figure A3.9, along with the other scenarios in the 2080s. The CGCM2_A1FI results indicate that the majority of climate envelopes projected for 2050s are consistent with climate envelopes presently found somewhere in western NA (the 2020s are not shown but were similar). During these time periods, upper elevations of the Southern Selkirk Mountains and mid elevations on the western sides of the North Arm of Kootenay Lake, and the Slocan and Lardeau valleys are marginal matches for presently occurring climate envelopes. However, with the increasing advance of climate change, by the 2080s many of the climate envelopes projected for lower elevations are evolving into combinations of climate variables that do not presently occur in western NA .

CAUTION: To assist BC readers envisioning the type of climatic environments that may occur in the future, the climate envelopes have been designated with names of the most similar ecosystems that currently exist in BC. Although these climate envelopes are described with ecosystem names that are familiar, it should not be assumed that the future ecosystems that will develop in these climate envelopes will be identical to ecosystems that readers are familiar with.

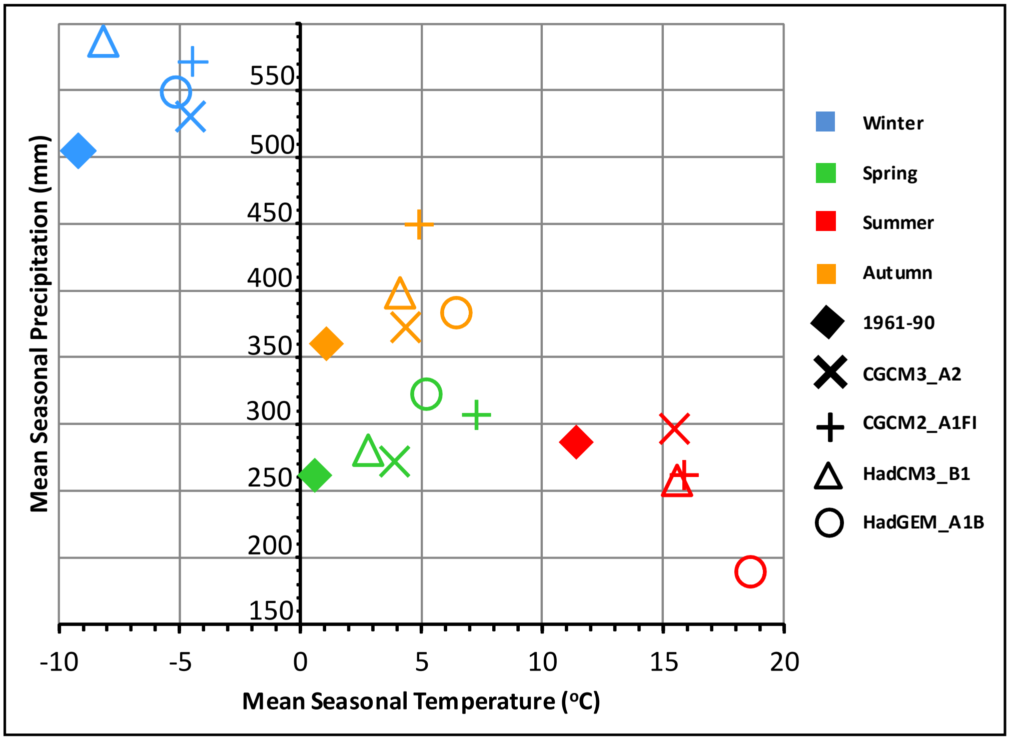


Figure A3.1. Seasonal climate variables for the reference period (1961-90) and the 2080s for four GCM/ emission scenario projections for the North Subregion.

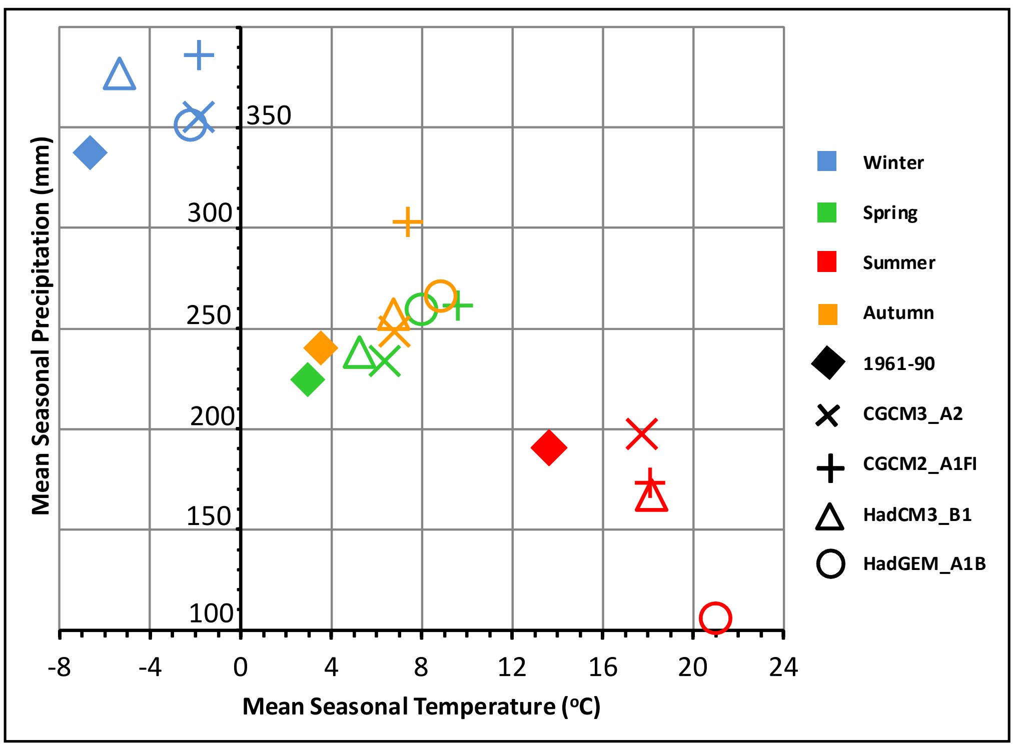


Figure A3.2. Seasonal climate variables for the reference period (1961-90) and the 2080s for four GCM/ emission scenario projections for the South Subregion.

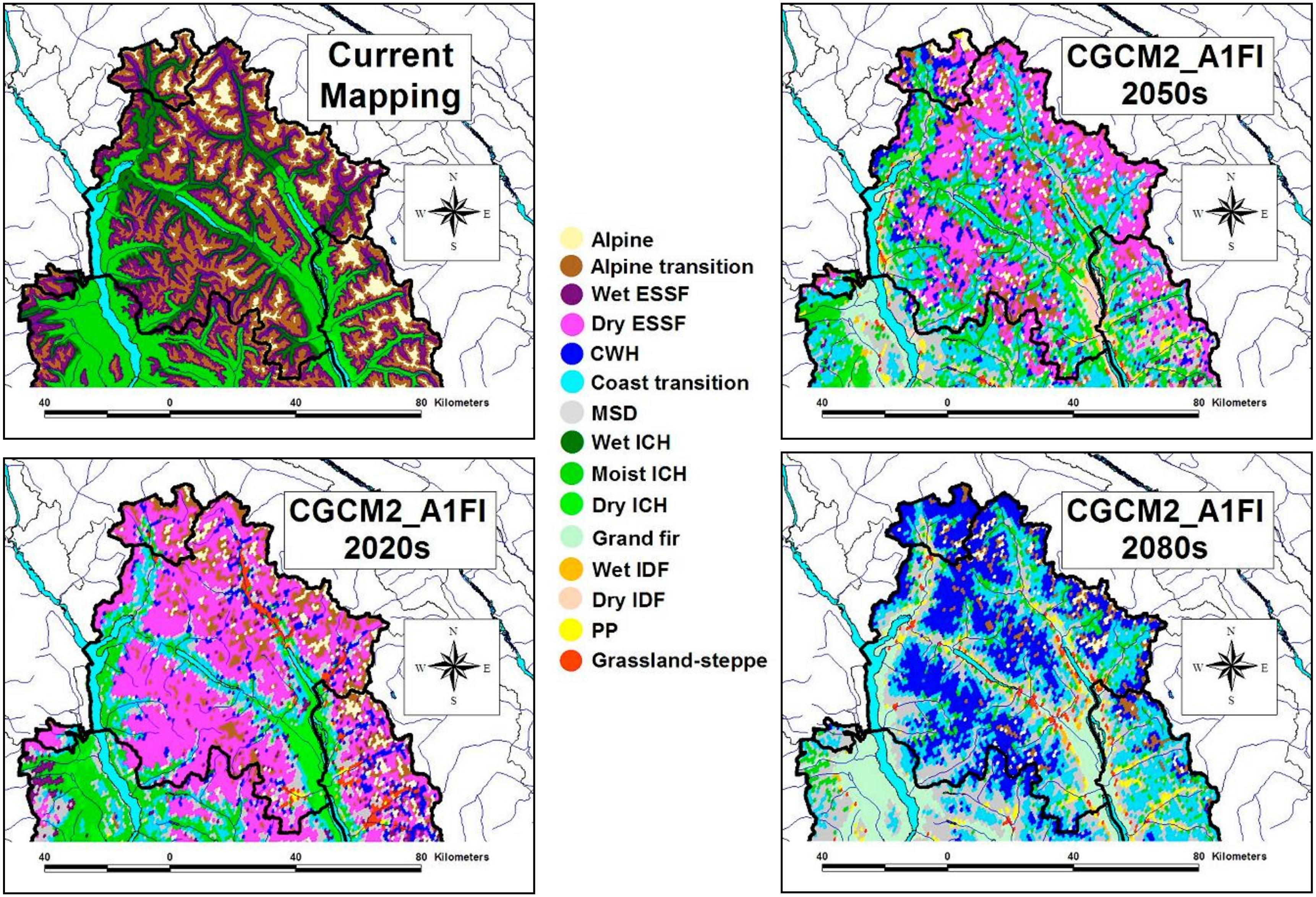


Figure A3.3. Projected shifts in bioclimate envelopes in the North Subregion for one GCM/ emission scenario combination; modeled with RandomForest and derived from various ecosystem classifications across western North America (Roberts and Hamann 2011, upubl. data).

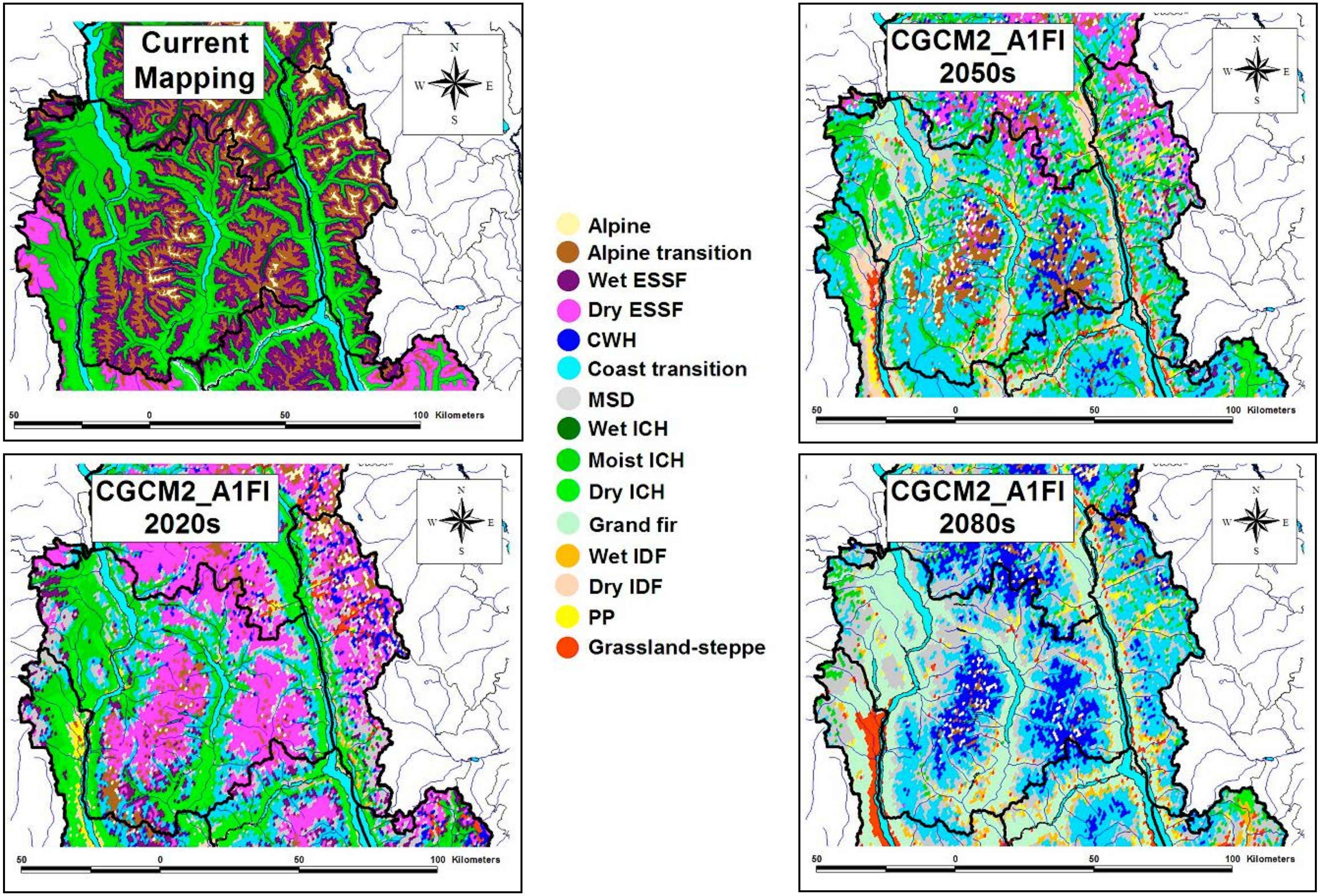


Figure A3.4. Projected shifts in bioclimate envelopes in the Mid Subregion for one GCM/ emission scenario combination; modeled with RandomForest and derived from various ecosystem classifications across western North America (Roberts and Hamann 2011, upubl. data).

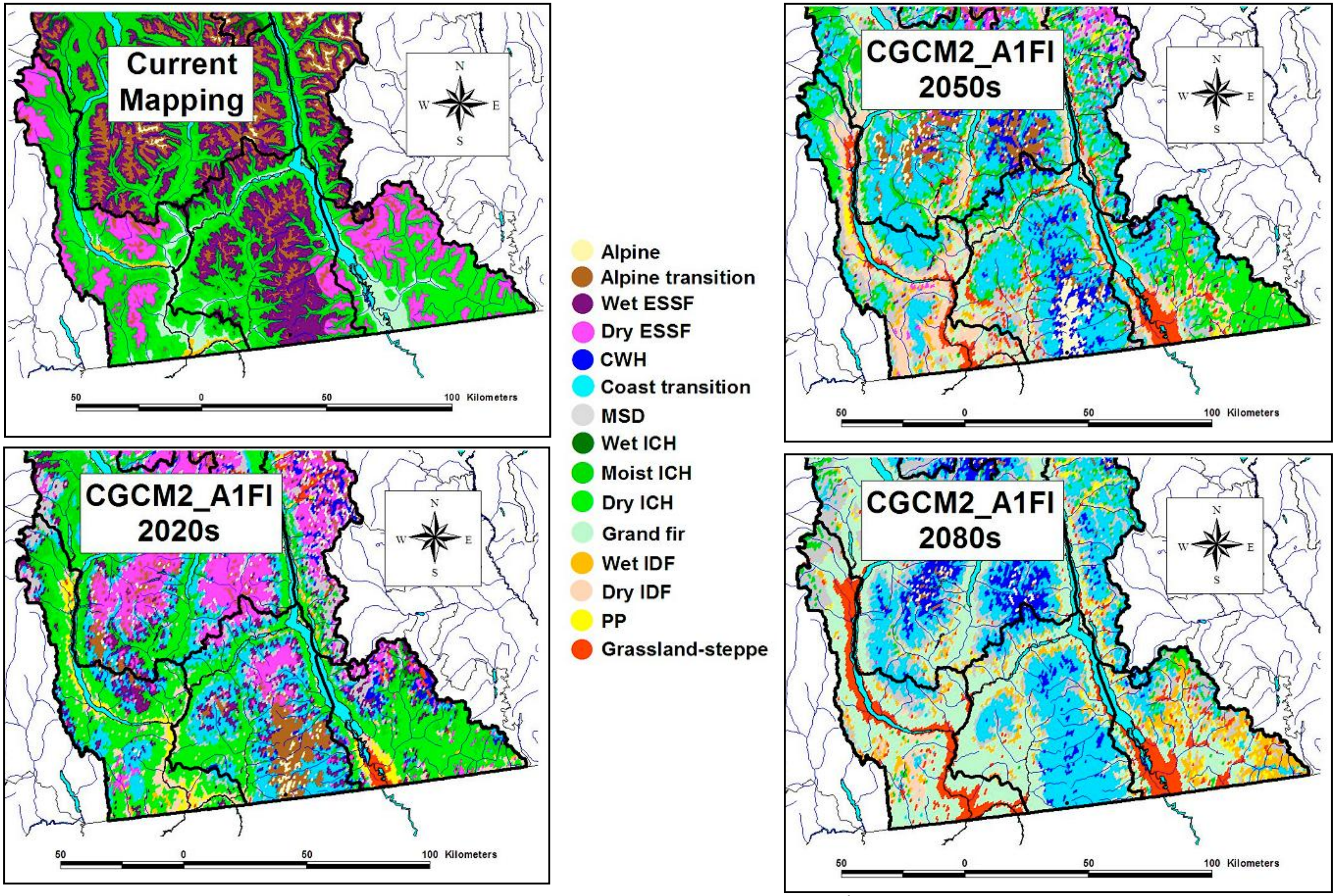


Figure A3.5. Projected shifts in bioclimate envelopes in the South Subregion for one GCM/ emission scenario combination; modeled with RandomForest and derived from various ecosystem classifications across western North America (Roberts and Hamann 2011, upubl. data).

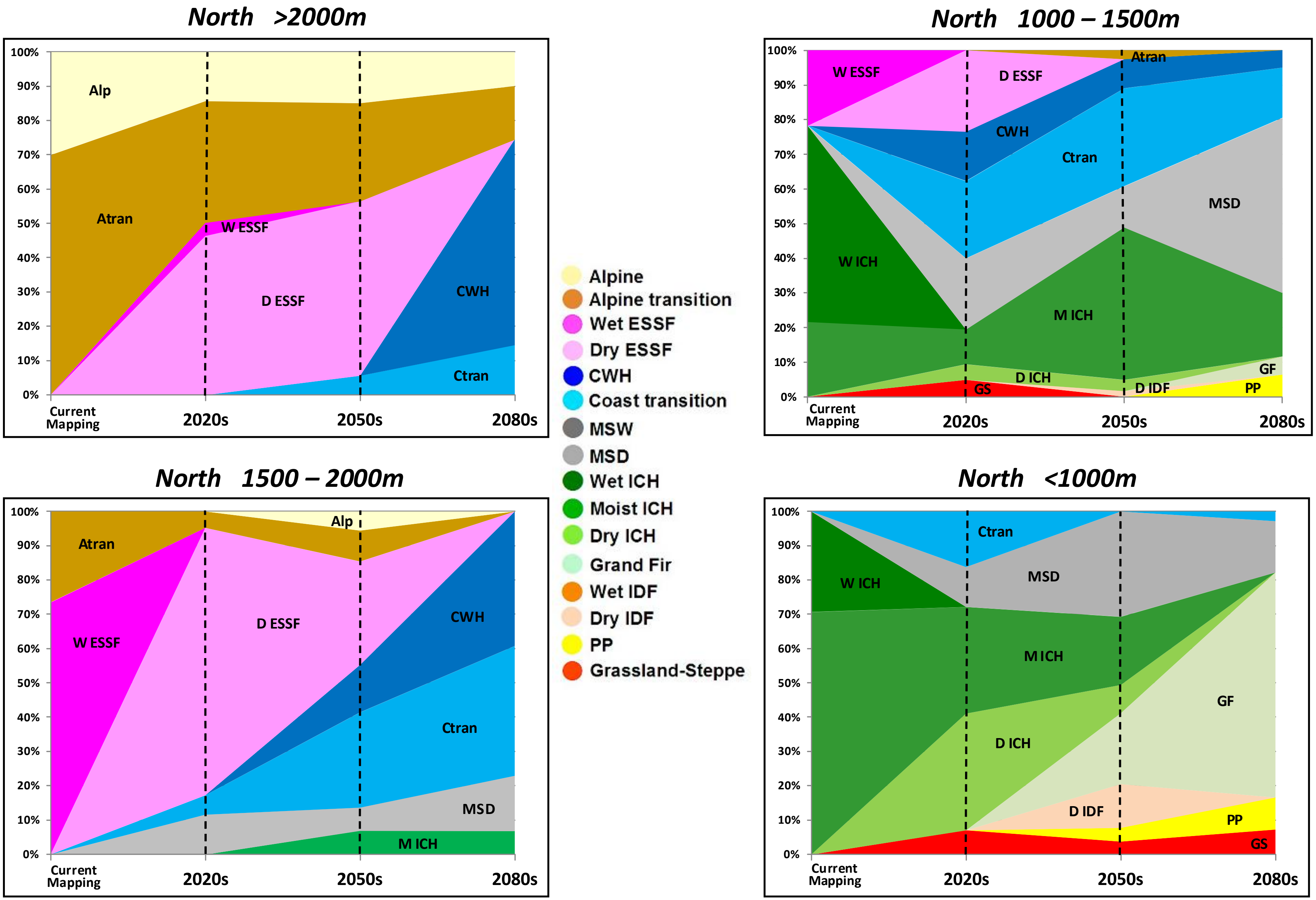


Figure A3.6. Bioclimate envelope shifts by elevation band in the North Subregion modeled with RandomForest and projections from the CGCM3 GCM and A1FI emission scenario (run 1).

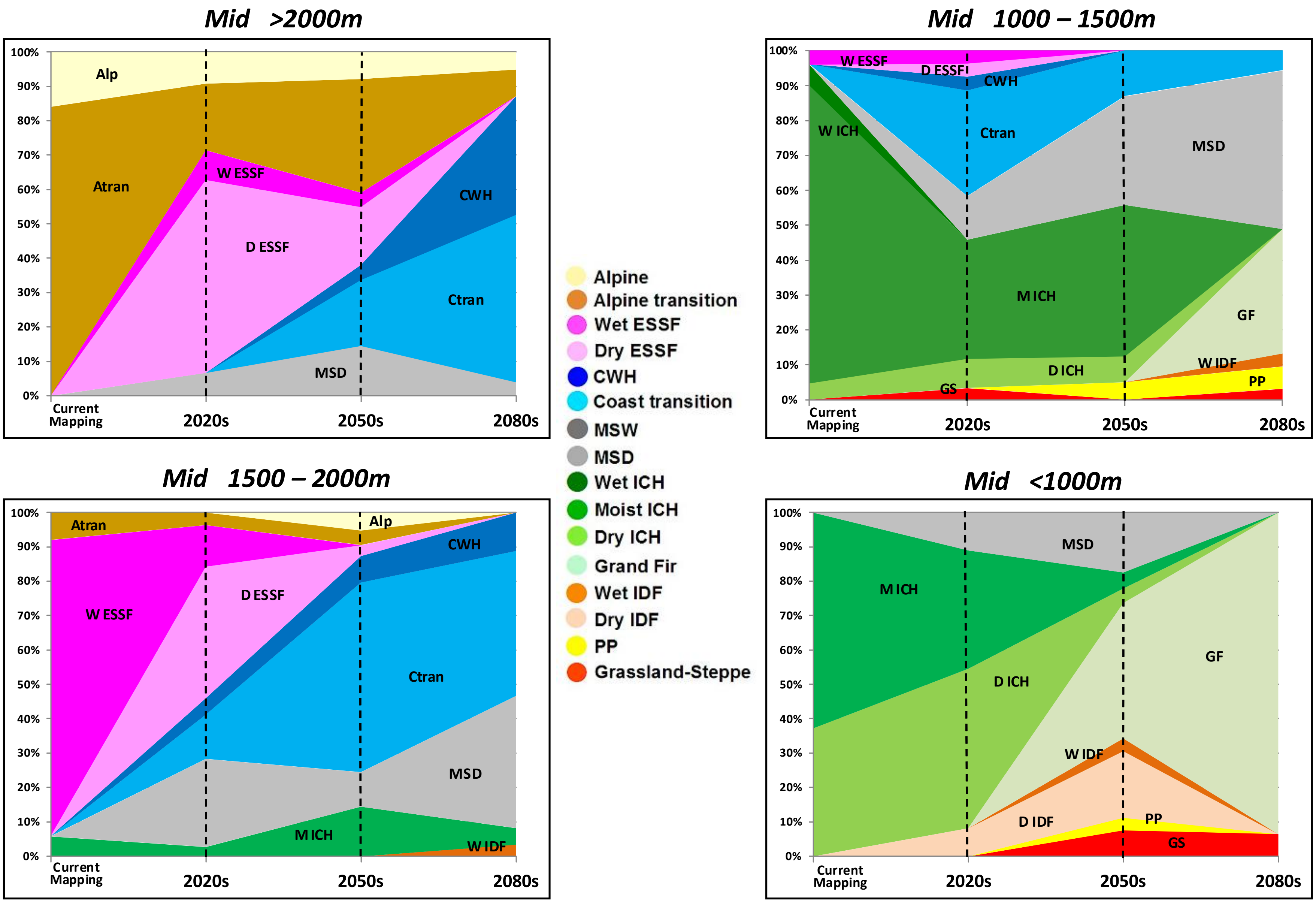


Figure A3.7. Bioclimate envelope shifts by elevation band in the Mid Subregion modeled with RandomForest and projections from the CGCM3 GCM and A1FI emission scenario (run 1).

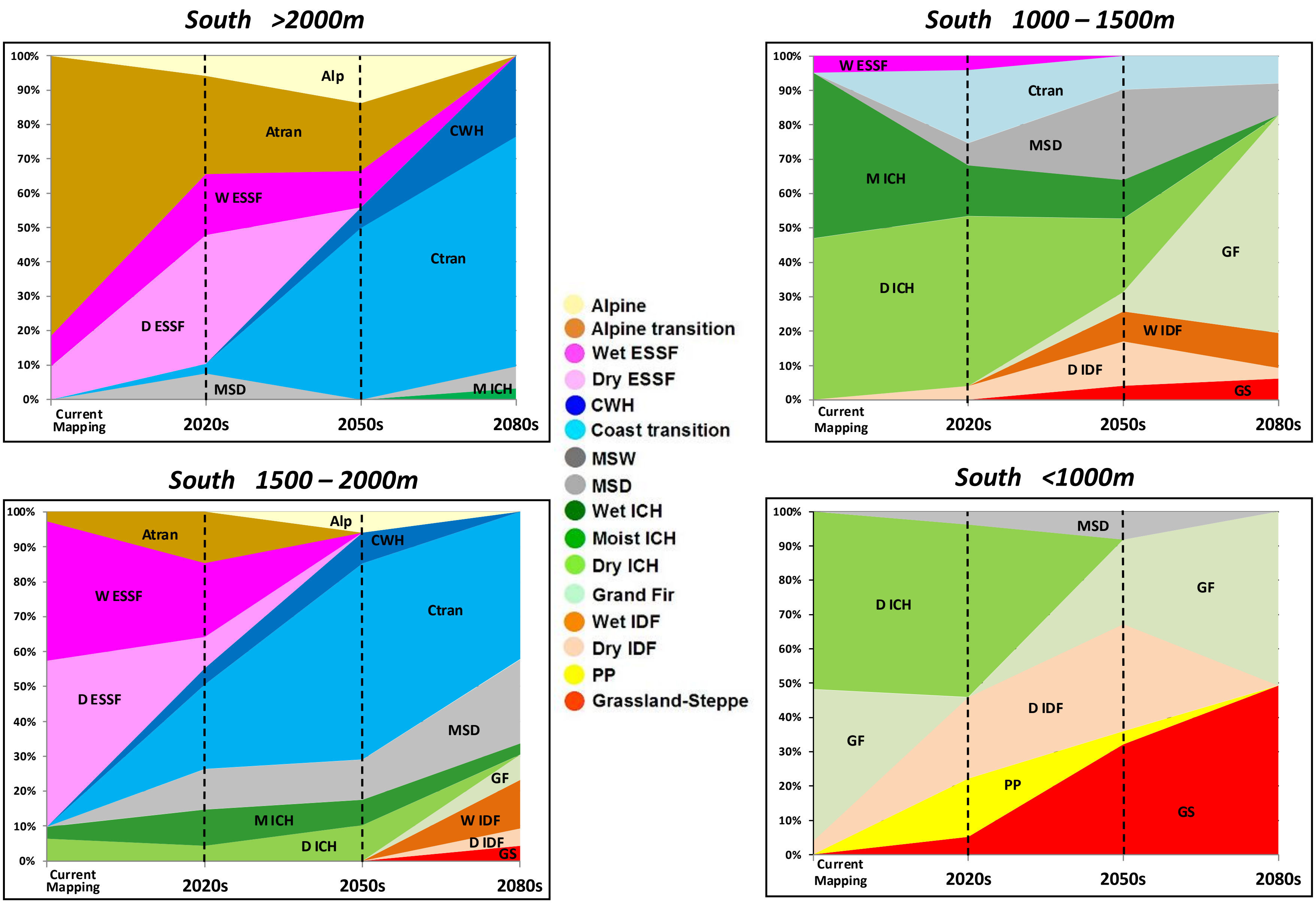
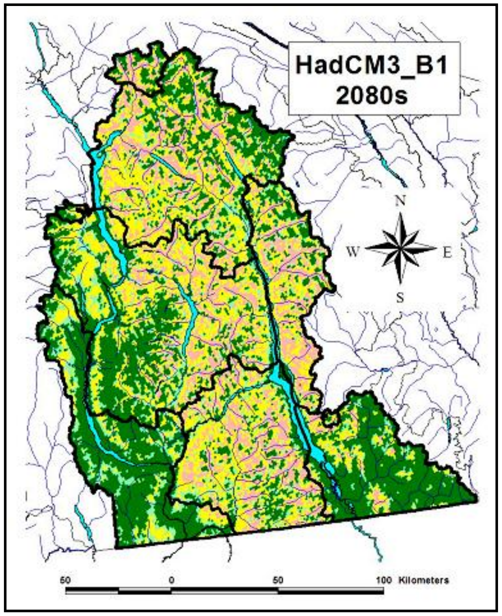
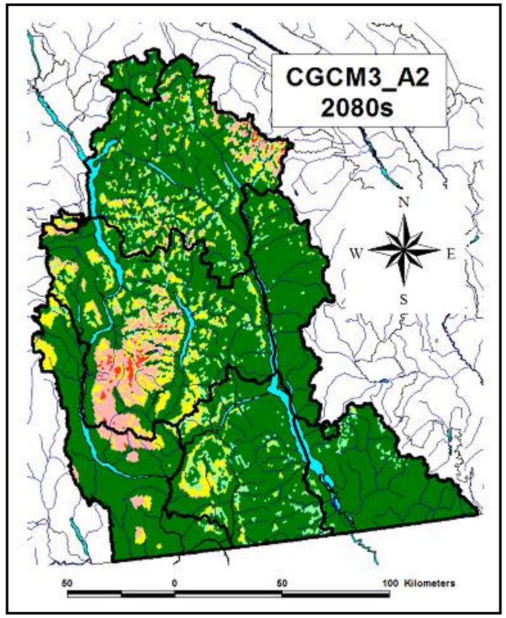
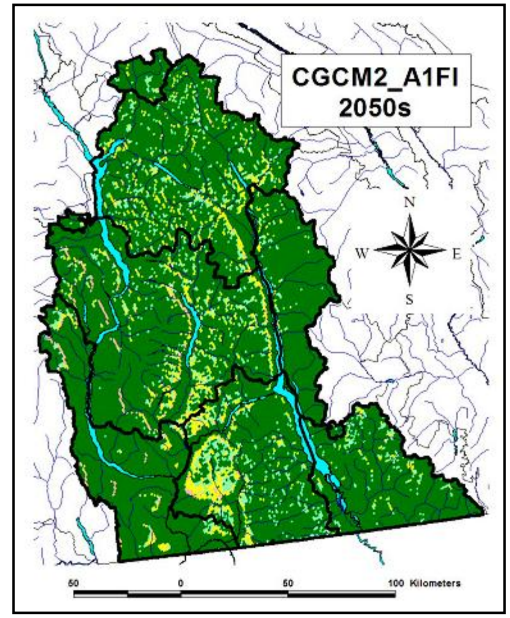
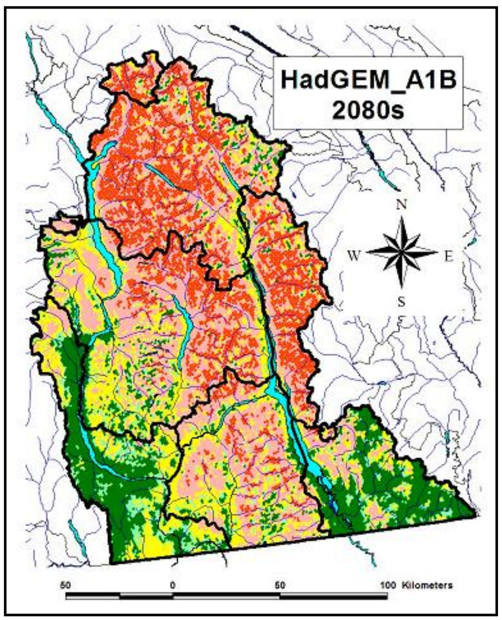


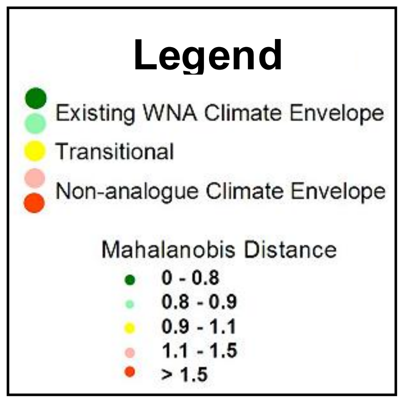
Figure A3.8. Bioclimate envelope shifts by elevation band in the South Subregion modeled with RandomForest and projections from the CGCM3 GCM and A1FI emission scenario (run 1).











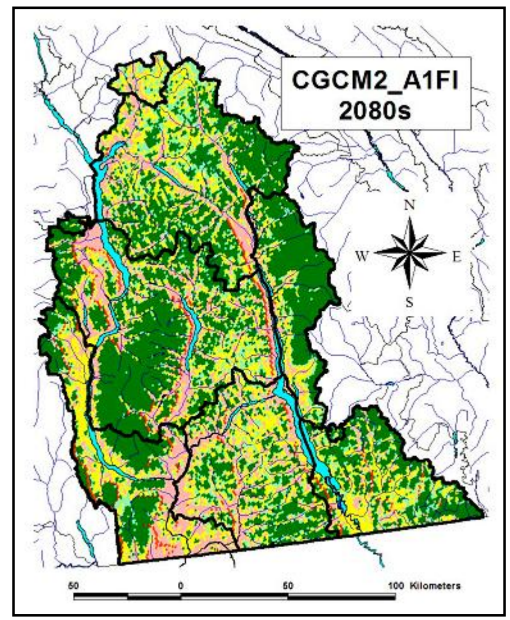


Figure A3.9. Projected occurrence of non-analogue bioclimate envelopes for four climate scenarios, and two time periods. These represent the potential for occurrence of novel ecosystem climate niches with no present analogues in western North America.

Table A3.1. Summary of projected ecosystem climate envelope shifts over the coming century based on results from RandomForest analysis and the CGCM2_A1FI-r1 GCM/ emission scenario combination.

	Current Mapping	2020s	2050s	2080s
North <1000m	Dominantly Moist ICH with some Wet ICH	Mostly Dry and Moist ICH with some Ctran and MSD; Dry ICH in the lower Lardeau and Duncan Valleys; minor GS in the mid Duncan Valley and lower Glacier Creek	Mix of MSD and Dry and Moist ICH; minor Dry IDF in the Lardeau Valley; minor GS, PP and GF south of Beaton	Mainly GF; some MSD in upper Duncan and Trout Lake area; very minor scattered PP, GS and Ctran
North 1000-1500m	Mainly Wet ICH with some Moist ICH and Wet ESSF	Mostly a mix of MSD, Ctran and Dry ESSF; some CWH in side valleys; some Moist ICH; GS in the mid Duncan Valley	Mainly Moist ICH and Ctran with some MSD; minor CWH in side valleys; very minor Dry IDF, Dry ICH and Atran	Mainly MSD; some Moist ICH and Ctran, mainly in the Purcells; very minor scattered PP, GF and CWH
North 1500-2000m	Dominantly Wet ESSF with some Atran	Mainly Dry ESSF; some MSD; very minor Ctran and Atran	Mostly Ctran and Dry ESSF with some CWH; minor Moist ICH, MSD, Atran and Alp	Mainly CWH and Ctran; some MSD; minor Moist ICH, mainly in the Purcells
North >2000m	Mainly Atran with some Alp	Mix of Dry ESSF and Atran; some Alp; very minor Wet ESSF	Mainly Dry ESSF and Atran; some Alp; minor Ctran	Mainly CWH; some Atran; minor Ctran and Alp, mainly in the Selkirks
Mid <1000m	Dry and Moist ICH	Mainly Dry and Moist ICH; some MSD and Dry IDF scattered along Kootenay Lake and Arrow Reservoir	Mainly GF with some Dry IDF and MSD; minor scattered GS; very minor PP, Wet IDF and Dry and Moist ICH	Dominantly GF; very minor scattered GS
Mid 1000-1500m	Dominantly Moist ICH with very minor Dry ICH; very minor Wet ICH and Wet ESSF in the Monashees	Mainly Moist ICH and Ctran with some MSD and Dry ICH; very minor Dry and Wet ESSF and CWH; very minor GS in valley bottoms of the Purcells	Mainly Moist ICH and MSD with some Ctran; very minor PP and Dry ICH	Mainly GF and MSD with minor Ctran and PP; very minor scattered GS and Wet IDF
Mid 1500-2000m	Dominantly Wet ESSF with minor Moist ICH and Atran	Mainly Dry ESSF and MSD; some Ctran and Wet ESSF; very minor M ICH and Atran; very minor CWH in the Purcells	Mainly Ctran; some Moist ICH and MSD; minor CWH, Dry ESSF, Atran and Alp	Mainly MSD in the Monashees; mixed MSD, Ctran and minor CWH in the Selkirks, Ctran and MSD in the Purcells; very minor Moist ICH and Wet IDF
Mid >2000m	Dominantly Atran and some Alp	Mainly Dry ESSF and Atran; some Alp and MSD; minor Wet ESSF in the southern Valhallas and Monashees	A mix of Atran, MSD, Ctran and Dry ESSF; very minor Alp and CWH; CWH, Atran and Alp mainly in the Selkirks	Mainly Ctran in the Purcells and Monashees; some CWH and Atran in the Purcells; mainly CWH in with minor, MSD, Atran and Alp in the Selkirks

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Table A3.1 continued

	Current Mapping	2020s	2050s	2080s
South <1000m	Dominantly Dry ICH and GF with very minor Dry IDF; GF near Creston, in the West Arm and along the Southern Columbia River; Dry IDF near Deer Park and in the Pend d'Orielle Valley	Mainly Dry ICH; PP and Dry IDF along the Columbia River south of Faulquier to the US and in the Pend d' Orielle; GS, PP and Dry IDF in the Creston area; very minor MSD in the West Arm	Extensive Dry IDF and GS and PP along the Columbia River and in Sheep Creek; GS and Dry IDF in the Creston area; the remainder a mix of GF and minor MSD	Extensive GS along the Columbia River, in the Pend d' Orielle Valley and in the Creston area; GF in the remaining areas
South 1000-1500m	Dominantly Dry and Moist ICH with very minor Wet ESSF	Mainly Dry ICH with some Ctran in the Selkirks; some Moist ICH and very minor scattered MSD and Wet ESSF	Some Dry ICH in the Purcells and MSD elsewhere; minor Moist ICH and Dry and Wet IDF, GF and Ctran; very minor GS	Mainly GF; minor MSD; minor Wet IDF and GS in the Purcells; minor Ctran in the Selkirks, minor Dry IDF in the Monashees
South 1500-2000m	Dominantly Dry and Wet ESSF with minor Dry ICH, Moist ICH and Atran; Dry ESSF in Monashees and Purcells; Wet ESSF in the Selkirks	Mainly Ctran and Wet ESSF; some Moist ICH, MSD and Atran; minor Dry ICH, CWH and Dry ESSF	Mainly Ctran; some MSD in the Monashees; minor Dry and Moist ICH in the Purcells; minor CWH and minor Alp in the Selkirks	Mainly Ctran in the Selkirks and mainly MSD in the Monashees and Purcells; some Wet IDF, mainly in the Purcells; some GF in the Monashees; minor Dry IDF in the Monashees; minor Moist ICH in the Purcells
South >2000m	Dominantly Atran and minor Dry and Wet ESSF	Mainly Dry ESSF throughout and Atran in the S. Selkirks; minor MSD and some Wet ESSF; very minor Ctran and Alp	Mainly Ctran, with some Atran and Alp; minor CWH and Wet ESSF; CWH mainly in the Selkirks	Mainly Ctran with some CWH, mainly in the Selkirks; very minor Moist ICH and MSD

[i] Although disturbance regimes were not modeled directly, each of the bioclimate envelopes and corresponding ecosystems can be linked to distinctive disturbance regimes that are currently associated with those ecosystems.